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An Evolutionary Framework for Experimental Innovation

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ABSTRACT

This paper presents an evolutionary view of technological and scientific innovation, and describes the role of experimentation in both. A stated policy for the Australian Department of Defence (reflecting the defence policies of other countries, including the United States) is to use the methods of empirical science to inform the innovation of the Defence Force. This paper describes what might be meant by "the methods of empirical science", and how such methods might be employed to improve military forces. We show how an evolutionary view both describes much of the scientific and technological innovation process, and provides guidance on how to move to the future. Historical case studies of technological and scientific innovations, and structural considerations, are used to justify such a view. A description of some of the tools of military experimentation is given, and it is shown how these fit within an evolutionary framework. Finally, the evolutionary framework is used to analyse some of the perennial debates about innovation, such as the role of revolution, the place of leadership and the search for optimal solutions.

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EXECUTIVE SUMMARY

This paper presents an evolutionary view of technological and scientific innovation, and describes the role of experiment in both. A stated policy for the Australian Department of Defence (reflecting the defence policies of other countries, including the United States) is to use the methods of empirical science to inform the innovation of the Defence Force. In such a context, it is helpful to understand what might be meant by "the methods of empirical science", and how such methods might be employed to improve military forces.

This document explores innovation in technology and science, and shows how an evolutionary view describes much of the innovation process, and provides guidance on how to move to the future. The evolutionary view is taken directly from the biological sciences, and applied specifically to technological and scientific change. Historical case studies of technological and scientific innovations, and structural considerations, are used to justify an evolutionary description of the innovation process that takes place within these domains. We also show how an evolutionary framework adds value to the process of innovation.

The paper gives an overview of what science is by exploring the chief historical developments in the philosophy of science over the past 400 years. It also gives a brief description of the limits to scientific knowledge that were identified during the twentieth century. An evolutionary model is then applied to science, and we show how the characterisitics of scientific method and experimentation fit within an evolutionary framework. Specifically, it accounts for why inductivist and falsificationist approaches are typical aspects of scientific method.

A description of some of the tools of military innovation is given, and it is shown (1) how they conform or otherwise to the methods of empirical science, and (2) how they provide value within an evolutionary structure.

Finally, the evolutionary framework is used to analyse some of the perennial debates about innovation, such as the role of revolution, the place of leadership and the search for optimal solutions.

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1 Introduction

1.1 Innovating in a Time of Unprecedented Change

"We are living in a time of unprecedented change." This statement, or ones like it, appear frequently in defence forward planning literature, and indeed in much western literature outside the defence community. In general it is a true statement because the world always changes, and the world is never the same as it was at any previous time. The rhetorical intention of such "unprecedented change" statements is to persuade the hearers to adopt a proposed policy, or system as a solution to a problem brought about by the unprecedented change, and to discard conventional solutions that may have worked in the past. Here we are interested in modern human warfare, and how best to make sure that we are on the winning side in the near future, or about twenty years in the future. A twenty year time span is generally thought to be a fruitful area of consideration because it lies between a 5–15-year future that will be largely limited by current plans and budgets, and a vaguer future, 30 or more years hence, that most people feel to be too far ahead to predict.

Accepting the fact that we live in a changing environment, the question this paper seeks to address is how to understand technological change, including change in military technology. The model I propose is based on ideas of evolution, particularly as applied to biological systems, including extended phenotypes. I will justify a view of the military that sees it as a technological extension of the human organism, and which evolves in a way similar to biological systems. I will also try to justify an evolutionary view of science—frequently seen as a means to successful innovation. By understanding how evolutionary principles apply to scientific and technological innovation, I hope to promote an overarching evolutionary framework for military innovation.

1.2 Method of Argument

This paper proposes an evolutionary view of technological, scientific and military change. Such an evolutionary view stands in contrast to a revolutionary view of change in these areas. In the revolutionary view, important changes are seen to be dominated by large discontinuous innovations brought about by heroic, sometimes famous, inventors. Legendary stories surround these inventors, and provide memorable images of how their genius was inspired. Isaac Newton contemplating an apple, and James Watt contemplating a boiling kettle, are two examples. These geniuses are seen as heralds of a new age, introducing changes unrelated to their present or past circumstances. The metaphor of political revolution is applied to famous names. For example, Nicolaus Copernicus is thought to have brought about the rise of modern science—the Copernican Revolution—by proposing the sun-centred model of the planets, and James Watt is thought to have brought about the Industrial Revolution by inventing the steam engine. In recent years some have interpreted the effect of information technology in revolutionary terms, using labels such as the Information Age (for western culture generally) and the Revolution in Military Affairs (in western military thought). There are top-level calls for revolutionary change, arguing that evolutionary change will be insufficient for corporate or military survival in the face of a rapidly changing competition. Dombrowski and Ross have summarised some of these calls as follows:[1]

> transformation entails "discontinuous change,", not merely the incremental change typical of modernization. Risks are to be taken. Transformation is to result in fundamentally new, rather than merely improved, technologies and weapons systems, doctrines, and operational concepts. Revolutionary rather than evolutionary change is the objective. Marginal improvements in capabilities are to be rejected in favor of leaps ahead.

This paper will argue that scientific and technological innovations, including military innovations, are governed by evolutionary principles. The approach will be:

1. To show that each of the innovative systems (science and technology, including military technology) conforms to the evolutionary prerequisites identified by Gould (see next section), namely that:
   (a) Each system can be described as replication with variation; and
   (b) Individual elements within each system compete for survival in an environment.
2. To show, from historical case studies of particular examples, how changes in each system were in fact evolutionary—they can be seen as a set of continuous variations of pre-existing elements, and did not arise *ex nihilo*.

Before we use this method we need to understand evolution, using its role in biology as a model. We will use this understanding of evolutionary forces to develop a simple evolutionary model that highlights some of the properties of evolutionary systems.

2 Evolution

2.1 Summary of Biological Evolution

The evolutionary model of biological development is summarised well in the following words of Stephen Jay Gould:

> [N]o great theory ever boasted such a simple structure of three undeniable facts and an almost syllogistic inference therefrom. . . . First, that all organisms produce more offspring than can possibly survive; second, that all organisms within a species vary, one from the other; third, that at least some of this variation is inherited by offspring. From these three facts, we infer the principle of natural selection: since only some offspring can survive, on average the survivors will be those variants that, by good fortune, are better adapted to

[1] Peter J. Dombrowski and Andrew L. Ross, *Transforming the Navy—Punching a Feather Bed?* Navy War College Review, Vol. LVI, No. 3, 2003, online at http://www.nwc.navy.mil/press/Review/2003/Summer/art5-su3.htm

> changing local environments. Since these offspring will inherit the favorable variation of their parents, organisms of the next generation will, on average, become better adapted to local conditions.[2]

This statement of the principle of biological evolution is adequate for our purpose here.[3] The first of Gould's facts, that more offspring are produced than can survive, is a statement of the limited resources available to sustain a population. These resources comprise energy in various forms; as a biological organism is one that metabolises energy to grow, react to its environment, and reproduce. The limits on available energy mean that efficient users of energy will tend to reproduce more successfully than less efficient users of energy. Individuals having reproductive success are those that survive long enough to reproduce, and hence pass on their heritable traits to the next generation. Efficient use of energy can mean many things: efficient metabolic breakdown of food into stored or kinetic energy, efficient mechanical systems (muscles, bones, teeth), efficient energy storage systems (fat, fur), efficient use of the environment (for shelter, protection, hunting, hiding), efficient reproductive processes (mating, rearing, protecting the young), and so on. Given that biological organisms react to an environment of limited energy, and that these reactions themselves result from evolutionary processes, living things evolve interactions between other living things that tend to reproductive success. These interactions can be cooperative or competitive, depending on whether the cooperation or competition affect the probability of genetic survival.

Adaptation of evolving organisms takes place because (1) replication in reproduction is not exact, and (2) the environment changes. The possible sources of variation in replication are many. At the genetic level, variation can arise from mutation, recombination and gene flow. Competition for reproductive success selects a subset of organisms that pass on their traits to the next generation. In a fixed environment, the traits tending to an organism's reproductive success might not change. However, the environment of an organism includes its competitors, which have reproductive variation. Therefore, its environment is never fixed; even in an unchanging habitat, competition between varying reproducers can lead to evolution of the organism over time. And with fixed competitors, changes in an organism's habitat, due to climate change for example, can lead to evolution of the organism over time.

2.2 An Evolutionary Model

2.2.1 Population Model

To make explicit some of the factors governing evolutionary systems we consider a replication system consisting of a population of coloured dots. The system is illustrated in figure 1. At the beginning, the population consisted of 100 green dots of exactly equal colour. These we imagine as existing in an environment whose colour changes with time.

[2] Stephen Jay Gould, in *Evolution: The Triumph of an Idea*, Carl Zimmer, Harper-Collins, New York, 2001, p. xii.

[3] Other introductions to biological evolution are: Chris Colby *Introduction to Evolutionary Biology*, 1997, online at http://www.talkorigins.org/faqs/faq-intro-to-biology.html, and a list of sites is provided by the University of Nottingham at http://bioresearch.ac.uk/.

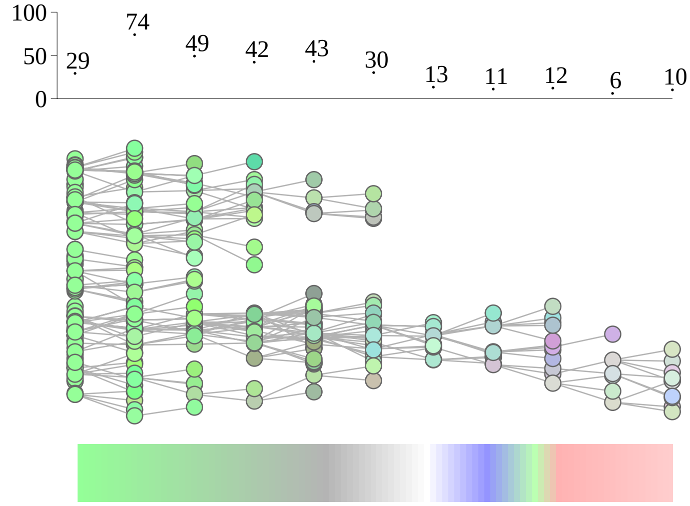


Figure 1: Evolution of a population of coloured dots

The colour of the environment as time proceeds is shown at the bottom of the figure. At a certain time, a certain number of dots had a chance at replication. The chance of replication depended on two things: the size of the population, and the population's colours. (The details of how replication and variation were handled in this model are given in appendix A.) Figure 2 shows how the number of potential replicators depended on the population size. (These quantities were calculated using equations A1 and A2.) At low populations the number of potential replicators increased in proportion to the size of the population, reflecting non-resource limited population growth. At large populations the number of potential replicators decreased exponentially, reflecting a resource-limited population. The potential replicators that actually replicated, in this model, were determined by calculating the differences between their colours and the colour of the environment at that time. The potential replicators that actually replicated were those that had the least colour discrepancy. We can interpret this as reflecting the effect of predation on the dots: those that could "hide" in the environment were more likely to replicate than those that could not. (Or, we could interpret it more generally as preferential survival of those that are most fit for their environment.) Having chosen the dots that could potentially replicate, the actual replication was carried out by assigning a random number of offspring to each of the actual replicators. The colours of these offspring were set equal to the parent colour with a slight random variation. The colour variation represented the variation in inherited characteristics of evolutionary systems. (The code used to implement this system is shown in appendix B.)

In figure 1, the surviving descendants of the initial population of 100 identically

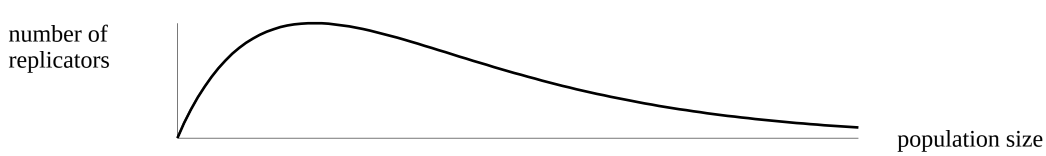
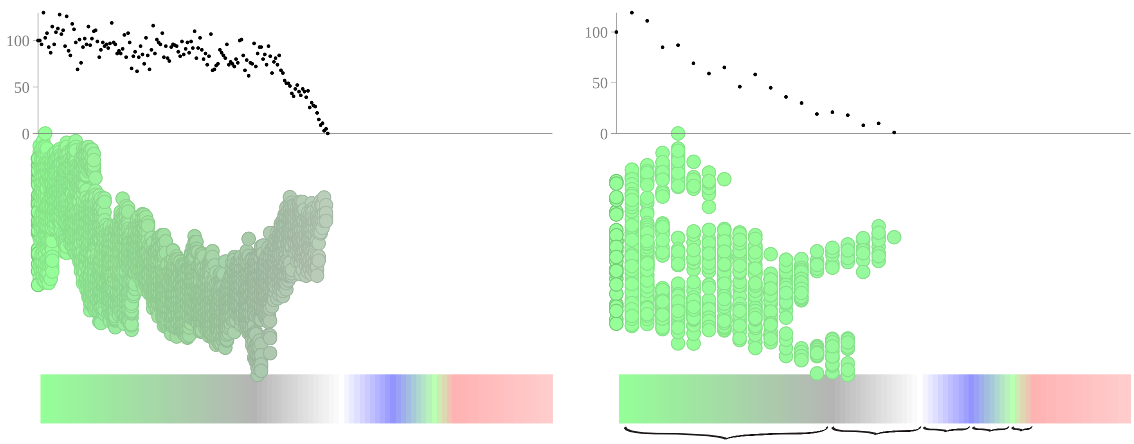


Figure 2: The dependence of the number of potential replicators on population size



Colour changes take place more rapidly as time ⟶ goes on. Numbers are time-steps required for major transitions.

40 20 10 7 4

Figure 3: Comparison of the evolution of the same initial population in the same environment, but with different time delays between generations (left: time delay = 0.35, right: time delay = 3)

green dots is shown at the left. To clarify the graphical presentation, the dots are shown randomly spread out in the vertical direction. The dots that replicated are shown connected to their offspring by gray lines. Each parent's offspring are placed vertically near the parent. The offspring then became a new generation that potentially replicated according to the same criteria as the parent generation. The total size of the population is shown at the top of the figure. In this case, the population split into two main branches; of these, the top branch died out before the end of the epoch in view, when the total population diminished from 100 members to 30. The remaining branch was able to survive until the end of the epoch, though it hardly thrived, remaining at a small total number.

2.2.2 Effect of Generation Time and Diversity

Figure 3 shows the effect of changing the time between generations. These two populations were initially identical, as were their environments. The amount of colour variation between parents and offspring was the same. The only difference between the two runs was that in one the time between generations was 0.35, and in the other it was 3. The unit of time corresponded to the minimum time allowed for a colour change in the environment. There were 100 colour changes in the epoch under consideration; the rapidity of the changes varied throughout, becoming more rapid until the transition to pink, and then a period of slow variation at the end, as shown in the lower part of figure 3. Looking at the total population size plotted at the top of each run, we see that the population with rapid generation (at left) sustained its numbers through the initial environmental change from green to gray, but could not adapt quickly enough during the transition to white. The population with slow generation (at right) was doomed from the start: its numbers steadily declined during the entire transition to gray. It is interesting to note that both populations endured until about the same time. The single measure of success, such as

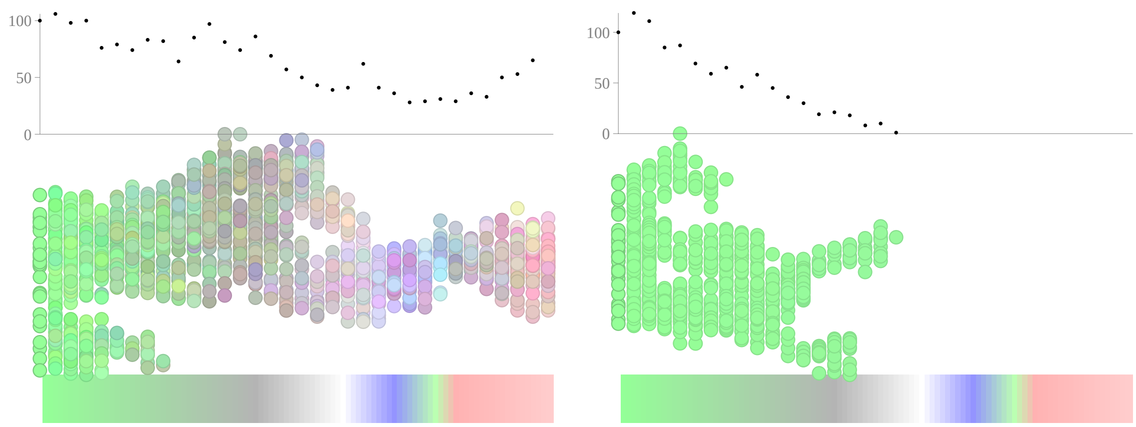


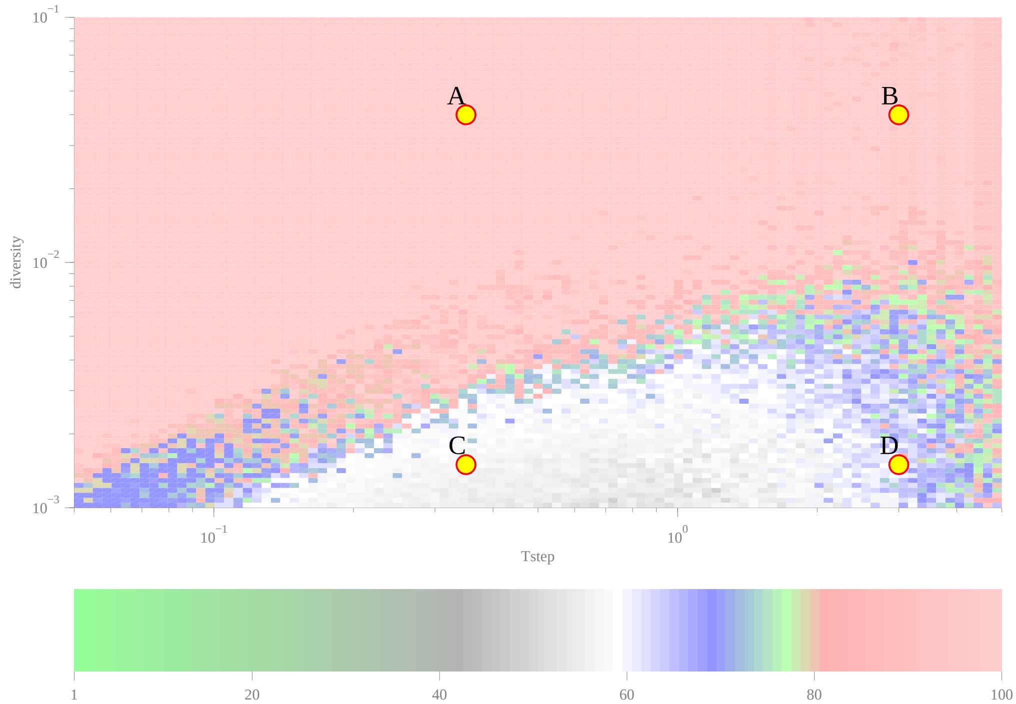
Figure 4: Comparison of the evolution of the same initial population in the same environment with the same generation time (3 time-steps), but with different allowed colour variations between parent and offspring (left: diversity = 4%, right: diversity = 0.15%)

"endurance", defined as the time at which the population became extinct, does not capture the full health of the system under study. The accumulated total of the population at each time step would be another potential indicator of "success".

(In figure 1 the generation time was 10, and the population in this case survived because of its diversity, see below.)

Figure 4 shows the effect of reproductive diversity on adaptability. The diversity is defined as the quantity v in equations A5–A7, and is a measure of the allowable difference of red, green and blue colour components between parent and offspring. The range of values allowed is between zero and one; in equations A5–A7 the colours are clipped to this range. By comparing the two cases in figure 4, we can see that increasing the diversity allows the population to adapt to the environment, even when the generation time is constant. The population shown at the right is unable to keep pace with changes to the environment and is in a continuous state of decline. The population shown at the left is able to survive well into the gray environment, begins to suffer during the transition to white, and recovers quickly after the final transition to pink.

Figure 5 shows the results of a detailed investigation of the effect of generation time and diversity on adaptability. At the top is a map of the adaptability of the population as a function of generation time (labelled "Tstep" on the x-axis) and diversity (on the y-axis; both axes are logarithmic. In this figure, the adaptability is defined as the time at which the population died out. If the population survived to the end of the run, then the adaptability was set to 100. At each value of generation time and diversity the model was run three times, and the mean time at which the three populations became extinct was recorded. This time is plotted on the map as the colour of the environment at the time of extinction, or as the final colour of the environment if the population survived to the end. For the four (Tstep,diversity) points highlighted by the yellow dots (A, B, C and D) in the adaptability map, plots of one of the evolution runs for that population are given in the lower part of the figure. Point A corresponded to a highly diverse, rapidly regenerating population that survived in large numbers through all changes in the environment up to



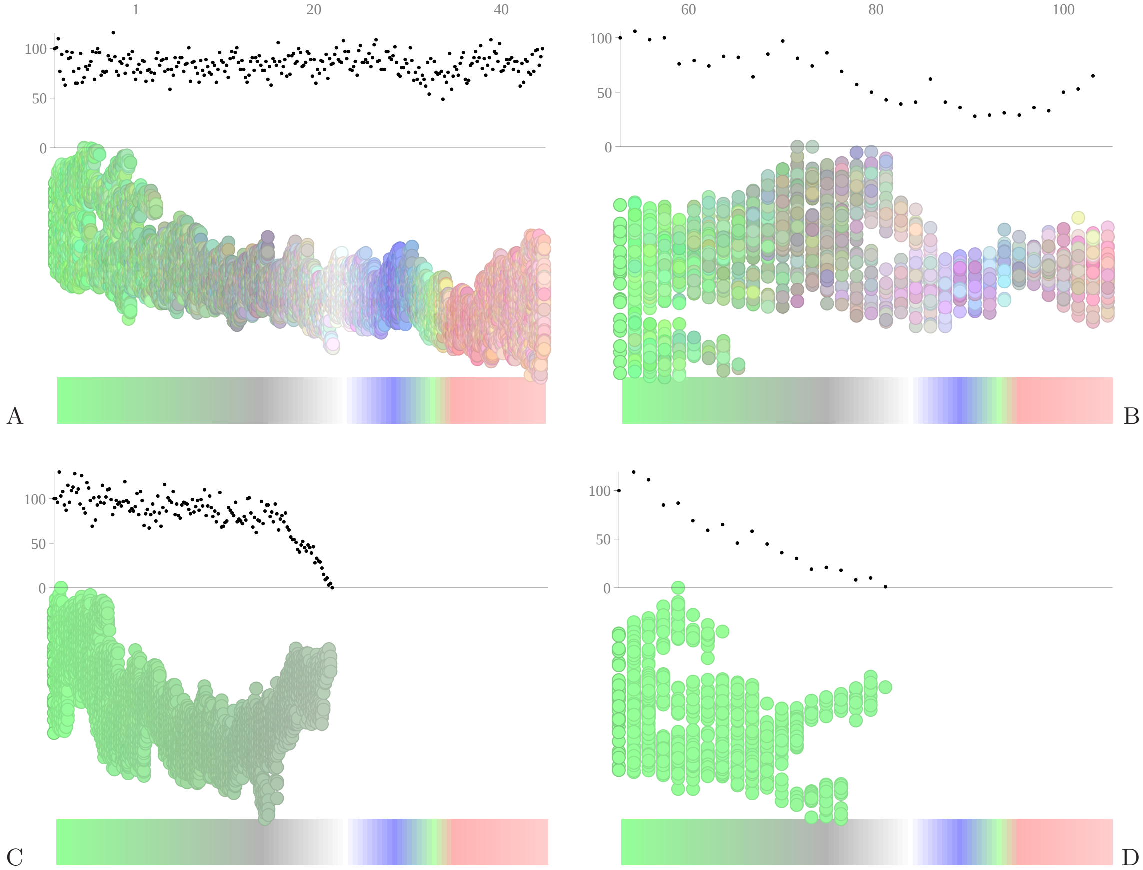


Figure 5: A detailed investigation of the effect of generation time and diversity on adaptability for the coloured dot evolutionary model

the end of the run. The population at Point B also survived to the end of the run but its population was less than that of point A because although it had the same diversity as point A, its regeneration time was longer. Points C and D illustrate that when the diversity is low, even a very rapid regeneration time will not allow the population to survive rapid changes in the environment; they both become extinct near the white to blue transition.

We will argue later that military experimentation can be seen as a way of increasing diversity and reducing the generation time for military innovation (see section 6.7, page 57).

2.2.3 Non-unique Success Measure

For many systems there is no unique or optimal solution for evolutionary fitness. In the previous example, the measure of fitness was to minimise the contrast between the dot colour and the environment colour. In this section we consider the result of changing the measure of fitness to be to maximise the contrast between the dot colour and the environment colour. Such a situation might correspond to the evolution in sexual reproducers of traits to attract a mate. An evolutionary model was set up with a constant environment of 50 percent gray. The only other change to the model was to invert the sort on colour distance so that the dots with most contrast survived, rather than the dots with the least contrast. Results of running the model twenty times are shown in figure 6. With colour defined as three levels of red, green and blue, there are eight possible colours that maximally contrast with 50 percent gray, namely red, green, blue, cyan, magenta, yellow, black and white (illustrated at bottom in figure 6). The system can evolve towards a population dominated by any of these eight equally valid solutions to the problem of standing out from the background. In each case, the initial population was comprised of 100 dots with 50% gray colour (red, green and blue components equal to 0.5). The dominant colour of the population at the end of the run depended on the cumulative effect of the random variations allowed between generations. Since the final dominant colour could swing wildly between the eight equally valid optima depending on small changes—both in the initial population and from one generation to the next—the system could be described as chaotic in a chaos theoretic sense. This contrasts with the situation described above where the measure of fitness was minimal contrast, and which led to a stable final population colour determined uniquely by the environment. Below we comment on the implications of cases of evolutionary systems where solutions are not unique.

3 Evolutionary View of Technological Change

3.1 General Observations

Innovation in technology, and more recently, in science have been among the most successful of human endeavours. Human technology and science have allowed modern human beings (*Homo Sapiens*) to spread to most areas of the Earth, make these areas habitable, and to produce a large population.[4] Examples of successful human technologies

[4] The earliest fossil evidence of *Homo Sapiens* was found in Ethiopia and dated to 160,000 years ago (see T. D. White, B. Asfaw, D. DeGusta, et al., *Pleistocene Homo sapiens from Middle Awash, Ethiopia*,

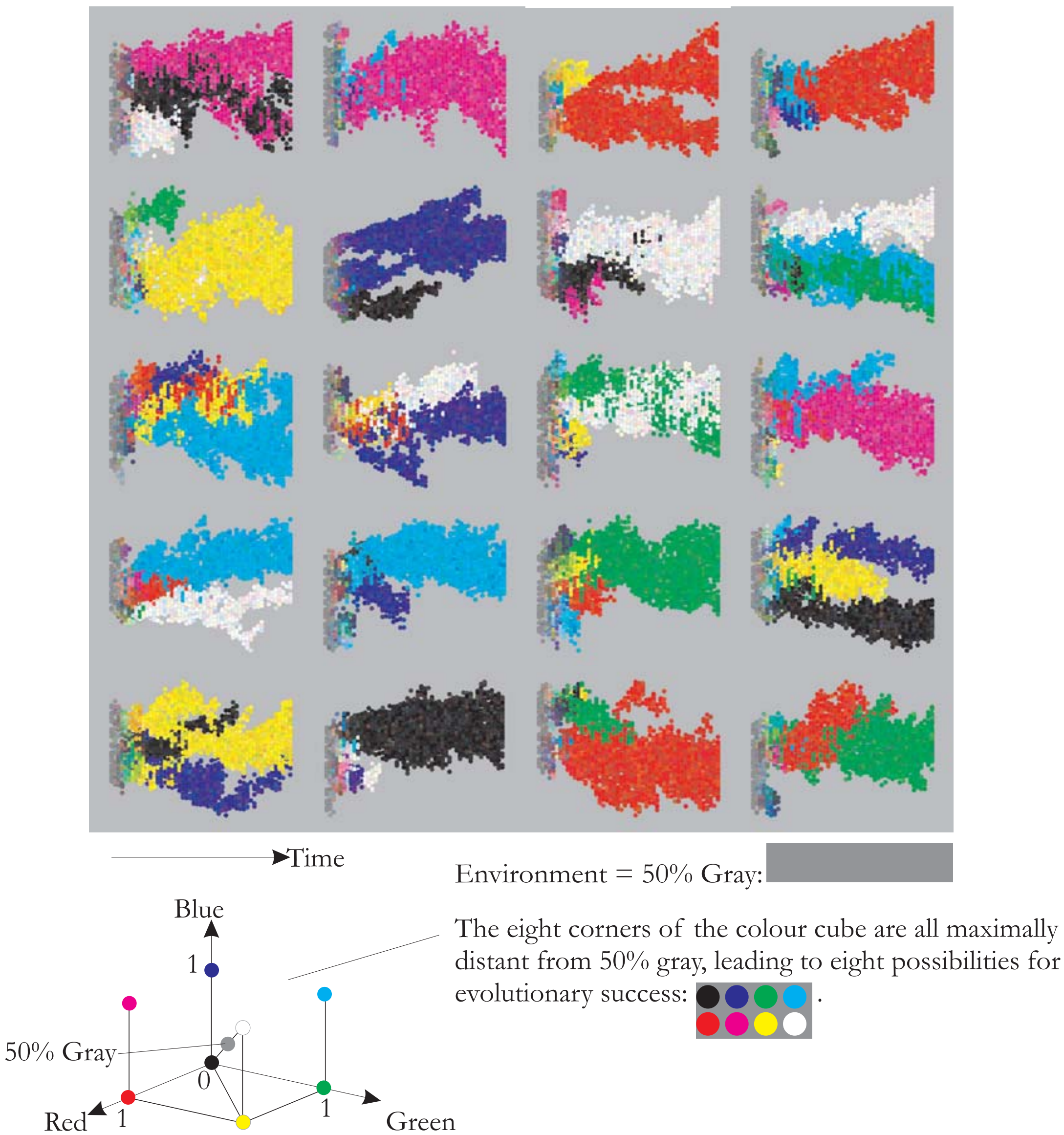


Figure 6: Twenty runs of the coloured dot evolutionary model in which the survival test selected those dots with the most colour difference from the constant gray environment

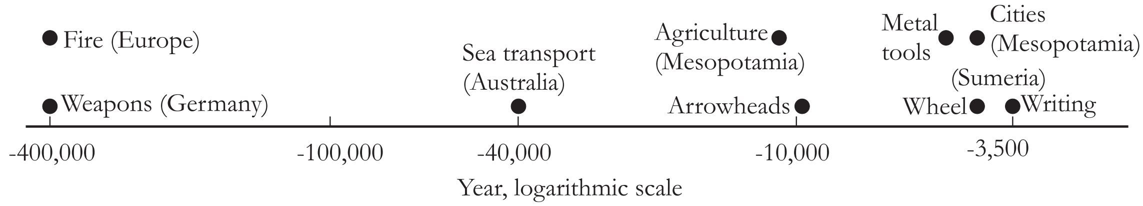


Figure 7: Examples of successful technological innovations

are shown in figure 7. The success of modern science—beginning, say, with Galileo—can be inferred from widespread use of its techniques in other domains, such as social science, psychology, economics, politics, and religion.[5]

Our focus in this section will be on technological artifacts: the actual objects made by humans for a purpose. All technologies are associated with behaviours, either in the individual or in the society that makes use of the technology. These behavioural or societal changes, though important, will not be treated here. More broadly, an artifact is a manifestation of information, the background knowledge, techniques, rituals, and so on, that are needed for people to make the artifact. Our focus here on the artifact follows Basalla.[6] For an argument that focuses on the techniques themselves, rather than the artifacts, as the units of analysis in an evolutionary understanding of technological change, see Mokyr.[7] Part of the argument will be that all new technological artifacts are related in a continuous way to either pre-existing technological artifacts or to "naturfacts": technologies available in the natural world.[8]

Another part of the argument will be that technological artifacts replicate with variation. They do not replicate themselves, as do biological organisms. Instead, people imitate the technology of their neighbours or predecessors, and, because artifacts wear out with use, new ones must be continually made. The useful life of an artifact corresponds to the generation time in the evolutionary model. The imitation process is not perfect: even attempts to exactly copy an artifact will lead to small variations. Attempts to use artifacts in different situations will highlight deficiencies which will be rectified by new

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Nature 423:742–747, 2003). Pre-human tools have been dated to 2.4 million years ago. Stone flake tools began to be innovated about 90,000 years ago. By 40,000 years ago, humans had spread to Europe, Asia and Australia (see Finn Nielsen, *Timeline of Human History*, online at http://www.fsnielsen.com/tln/timeline.htm). The current world population of 6.3 billion is higher than it has ever been.

[5]Religion is included in this list because some aspects of religion are argued to be scientific by their proponents. For example, in the United States of America creationism has been argued to be equally scientific as evolution by some, and ought to be included in school curricula. Others claim to have conducted scientific studies of the efficacy of prayer (http://abcnews.go.com/sections/Downtown/2020/Downtown_010813_remotehealing_feature.html). The Templeton Foundation "seeks to focus the methods and resources of scientific inquiry on topical areas which have spiritual and theological significance ranging across the disciplines from cosmology to healthcare". The point is that certain conclusion are said to be drawn in accordance with scientific methods and hence respectable.

[6]George Basalla, *The Evolution of Technology*, Cambridge University Press, 1988, p. 50). Some of the case studies in this section are taken from Basalla.

[7]Joel Mokyr, "Evolutionary phenomena in technological change," in John, Ziman (Ed.) *Technological Innovation as an Evolutionary Process*, Cambridge University Press, 2000.

[8]Naturfacts are elements of nature that serve as models for artifactual imitation (Ibid., p. 50). Some of the case studies in this section are taken from Basalla.

generations of artifacts. For example using a hammer to dress stone or to make shoes will result in variations of the hammer, just as using eyes in different biological niches will evolve new designs of eyes (see Figure 8). An artifact's shortcomings for a particular function will prompt the user to alter the artifact (or wish for one so altered) to correct the deficiency, constituting replication with variation. Patent applications describe the "prior art"—the status quo of the particular technology area—and how the applicant's claim improves upon it. Artifacts compete for successful replication. Making and using an artifact uses resources, so artifacts that consume less resources, either in its making or in use, will be preferred. The market economy makes explicit the choices people have in selecting among diverse but similar artifacts the one best suited for a particular use: people will invest in the least costly artifact that does the job, although sometimes "doing the job" is a multifaceted idea, not necessarily a simple measure of utility; for example, there are many considerations that go into buying a car. According to the US Patent Office, in FY 2003 they received about 330,000 utility, plant, and reissue patent applications, and 170,000 patents were granted.[9] Commentators estimate that only 10 percent of all patents granted are ever commercialised.[10] These facts indicate that only a small number of innovations successfully compete for survival in the marketplace of human utility.

3.2 Case Studies of Technological Innovations

We have given some general statements seeking to justify an evolutionary view of technological change. To strengthen the argument, we examine some specific cases to see if they conform to the evolutionary view, i.e. that the innovations formed a continuous development of pre-existing material, and that a competitive process was involved in their selection. Some of the case studies in this section—(1) Watt and the Steam Engine, (2) Edison and the Electric Light, and (3) Osage Orange and Barbed Wire—are taken from Basalla's *Evolution of Technology*. The first two expose the myth of the genius inventor and revolutionary technological change. The second is an illustration of an infrastructure technology. The last is a relatively modern example of technology imitating nature. Basalla gives many other examples, including stone tools, the wheel, the cotton gin, the internal combustion engine, the electric motor, the automobile, the transistor, the turbojet engine, supersonic transport aircraft, nuclear submarines and surface vessels, and an imaginary book-writing machine. In all cases, he shows how these innovations were evolutionary developments of prior artifacts, and involved a process of competitive selection. Other case studies in the evolution of technology are given by Petroski,[11] and include the dining fork, the paper clip, the zip fastener, Post-it notes, cans and can-openers, rope-sprung beds, McDonald's packaging, wheelbarrows, telephony, and others.

The study of the cruise missile is included as a relatively recent, specifically military technology, whose development is well documented.

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[9] Website of the United States Patent Office, http://www.uspto.gov/web/offices/com/annual/2003/040201_patentperform.html

[10] *Evolution of Technology*, pp. 69.

[11] Henry Petroski, *The Evolution of Useful Things*, Alfred A. Knopf, New York, 1993.

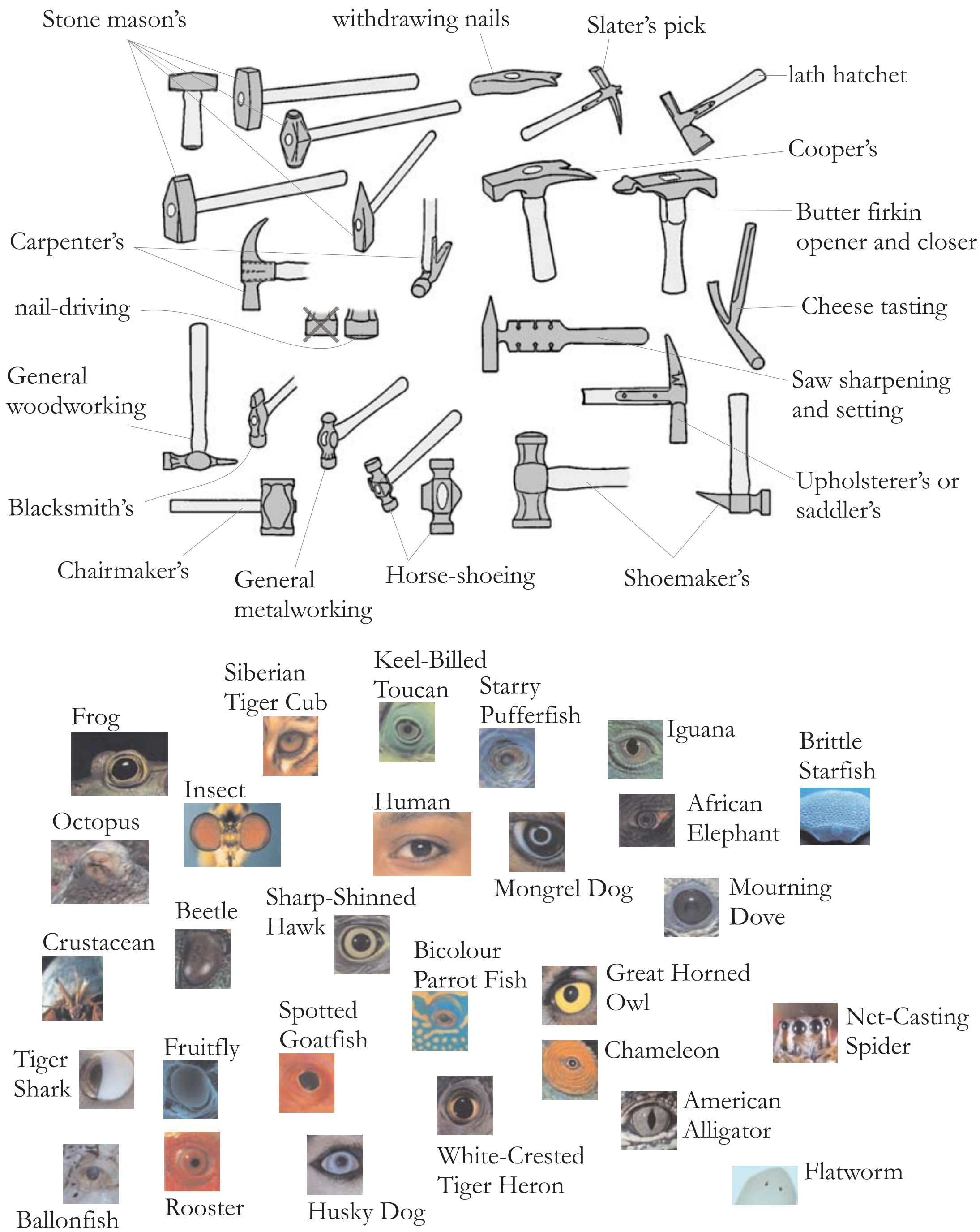

Figure 8: Adaptations of the hammer (top) to different functional environments arise from evolutionary forces that are analogous to those which led to adaptations of the eye to different biological niches (bottom). (Top figure adapted from Basalla, Evolution of Technology*, pp. 4–5, bottom figure adapted from Zimmer,* Evolution: The Triumph of an Idea*, cover art and p. 129, and other sources.)*

Figure 9: An allegorical illustration (ca. 1850) of a kettle inspiring James Watt to invent the steam engine (from Wolfgang Schivelbusch The Railway Journey*, Oxford, 1980, p. 5, reproduced in Basalla, p. 38)*

3.2.1 Watt and the Steam Engine

The steam engine, invented by James Watt, is often said to have been the trigger for the industrial revolution.[12] The legend of James Watt is that he was inspired to invent the steam engine after watching steam issue forcefully from a kettle's spout (see figure 9).[13] Watt's first completion of a successful full-sized steam engine was in 1775, but working steam engines of the Newcomen type had existed in England since 1712, some sixty years earlier, and were in widespread use. Watt had been asked to repair a small-scale model of a Newcomen engine in 1763. Watt modified the Newcomen engine by separating the condenser from the cylinder as shown in figure 10. Newcomen's was an atmospheric engine: a partial vacuum was produced by spraying cold water into a steam-filled cylinder. The pressure difference between the vacuum on one side of the piston and atmospheric pressure on the other gave rise to a force on the piston which moved to reduce the volume of the cylinder. Newcomen connected the moving cylinder to pumps that raised the water from deep coal mines. Watt realised that energy was wasted in continually re-heating

[12] A Google search revealed 4,650 references to pages containing the phrases "steam engine", "James Watt" and "industrial revolution", March 2004.

[13] *Evolution of Technology*, pp. 35-40.

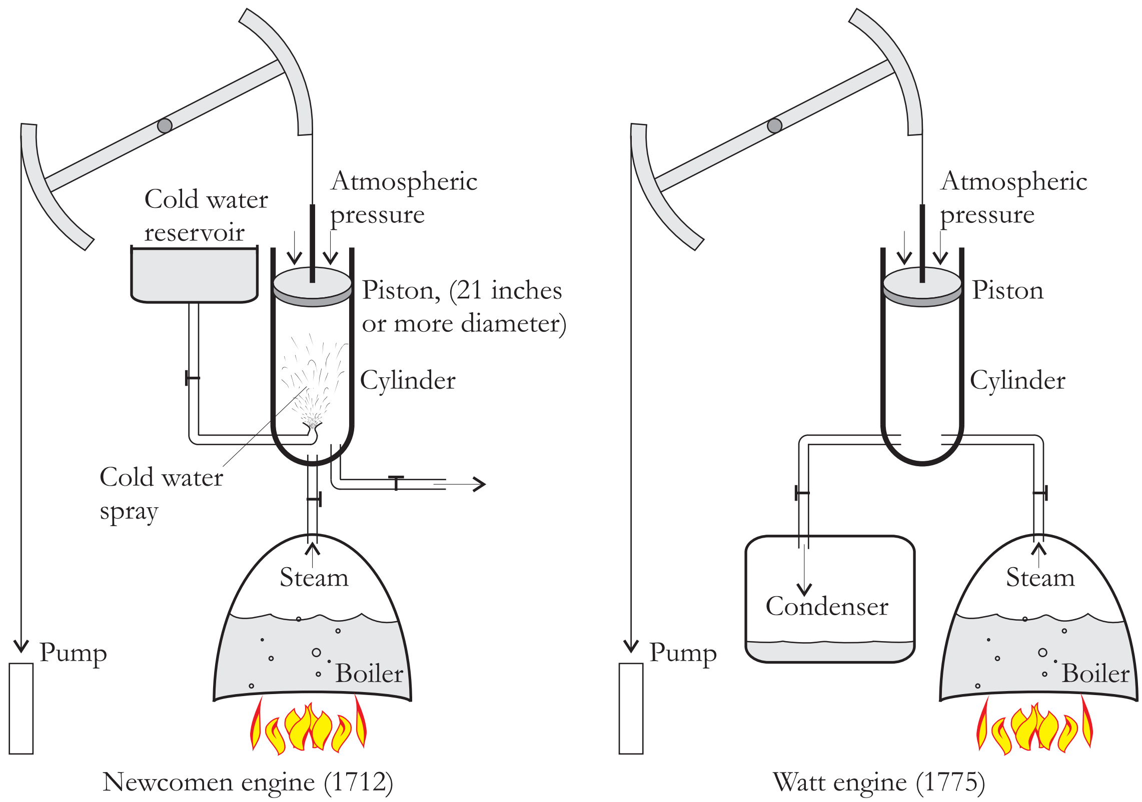

Figure 10: Watt's modification of the Newcomen steam engine was to replace the cooling mechanism of the cold water spray with a connection to a separate condenser, thus conserving the energy wasted in heating the cylinder itself during each cycle (adapted from James E. McClellan and Harold Dorn, Science and Technology in World History—An Introduction*, Johns Hopkins University Press, 1999, pp. 282, 284)*

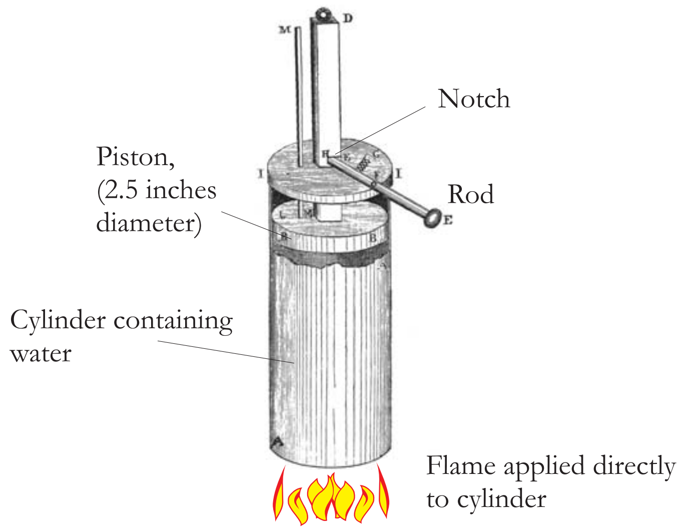

Figure 11: The experimental steam cylinder of Denis Papin (1690), from Evolution of Technology*, pp. 94*

the cylinder during each cycle after it was cooled by the water spray in the previous cycle. He allowed the cylinder to stay hot by eliminating the cold water spray, and instead allowing the steam to vent into a condenser chamber that was always kept cool. Watt's was an important contribution, which led to efficiency gains that allowed Watt engines to be situated away from coal mines. The crucial point is that Watt's modification was essentially an evolutionary development of existing material.

If Watt's engine was based on Newcomen's, then where did Newcomen's come from? Newcomen was an ironmonger who worked with a plumber assistant, and their work "evolved through trial and error".[14] Basalla traces[15] the development back to Denis Papin (1647–1712), a French scientist who experimented with steam, evacuated cylinders and pistons. His apparatus consisted of a piston in a cylinder containing a small amount of water. He pushed the piston to the bottom of the cylinder (see figure 11) until it touched the water in the bottom. He applied flame directly to the cylinder, boiling the water and filling the cylinder with steam, which slowly raised the piston. The piston was then immobilised by inserting the rod in the notch. The flame was removed and the cylinder allowed to cool slowly, condensing the steam to water and creating a partial vacuum in the cylinder. The rod was then removed, and the piston was forced into the cylinder by a strong force that Papin was able to measure. Papin published his work and suggested that his results could be put to use lifting material from mines, firing bullets, or moving ships without sails. In an English review of Papin's paper, it was summarised as "a method of draining mines", and Basalla argues that Newcomen was likely to have seen this review. Papin's contemporaries and predecessors also investigated evacuated cylinders, including von Guericke (1672), Robert Hooke and Robert Boyle (1675) who experimented with evacuated cylinders, vacuum pumps and applied forces. Galileo and

[14]James E. McClellan and Harold Dorn *Science and Technology in World History—An Introduction*, Johns Hopkins University Press, 1999, pp. 281).

[15]*Evolution of Technology*, pp. 92ff.

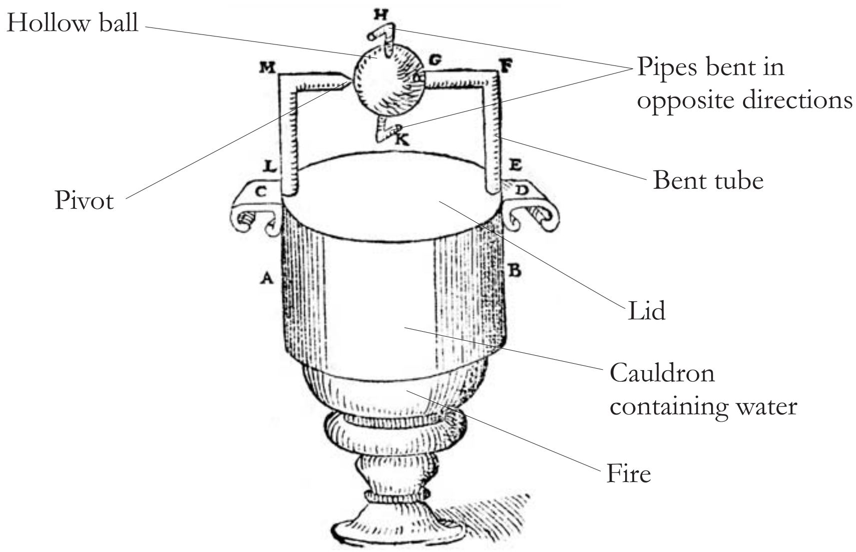

Figure 12: Description of a steam powered reaction turbine by Hero of Alexandria: "Place a cauldron over a fire: a ball shall revolve on a pivot. A fire is lighted under a cauldron, AB, . . . containing water, and covered at the mouth by the lid CD; with this the bent tube EFG communicates, the extremity of the tube being fitted into a hollow ball, HK. Opposite to the extremity G place a pivot, LM, resting on the lid CD; and let the ball contain two bent pipes, communicating with it at the opposite extremities of a diameter, and bent in opposite directions, the bends being at right angles and across the lines FG, LM. As the cauldron gets hot it will be found that the steam, entering the ball through EFG, passes out through the bent tubes towards the lid, and causes the ball to revolve . . . ". (Image from Spiritalium Liber*, Latin translation of Hero's Pneumatics, 1575, Urbino, Italy, online at http://www.iihr.uiowa.edu/products/history/hoh/hero.html, text from* The Pneumatics of Hero of Alexandria *Translated and edited by Bennet Woodcroft, London, 1851, online at http://www.history.rochester.edu/steam/hero/section50.html).*

Torricelli in 1643 had measured atmospheric pressure by showing that it was impossible to draw water up a pump with a piston for more than about 28 feet. Shortly after 1609, Salomon da Caus in England published a method for creating fountains by filling copper spheres with water and heating them, thus forcing the water out through pipes under pressure. Motion generated by steam pressure goes all the way back to Hero of Alexandria (ca. 100 C.E.) who described a steam powered reaction turbine in his *Pneumatics* (see figure 12). Basalla cites[16] two historical studies of the history of the steam engine, both highlighting the evolutionary nature of its development, one of which concludes: "the hidden pre-natal history of the reciprocating steam-engine [includes] currents of design . . . which went back many centuries before Newcomen and Watt. No single man was 'father of the steam-engine'; no single civilization either".[17]

Watt's innovation was by no means the single innovation that led to the industrial revo-

[16]Ibid., p. 40, see also, Richard L. Hills, *Power from Steam : A History of the Stationary Steam Engine*, Cambridge University Press, 1993

[17]Joseph Needham, *The Pre-Natal History of the Steam Engine*, excerpt online at http://www.newcomen.com/excerpts/prenatal.htm

lution. Though in 1800 five hundred Watt engines powered mines, mills and steamships throughout Britain, all of them were large installations that relied on the limited pressure of the atmosphere to drive them. By 1800 Richard Trevithick had developed a high pressure steam engine that was much more compact than the Watt atmospheric engine. Trevithick sought to compete directly with Watt by marketing his engine to mine and mill owners. He failed because mine and mill owners had already invested in Watt (and Newcomen) engines and were unwilling to scrap them, and because, to maintain his market share, Watt publicised the questionable benefits of the high pressure engine and exaggerated its reputation for being unsafe. Trevethick then tried to sell his engine for use in high altitude Peruvian mines, where reduced atmospheric pressure reduced the capacity of atmospheric engines, and maximised the benefits of the high pressure engine. Again he failed. In 1814 George Stephenson demonstrated a steam locomotive. Other technological factors involved in the massive series of changes called the industrial revolution included textile processing and iron smelting.

In this outline of the development of the steam engine, we have shown that Watt's contribution was an incremental (but important) evolutionary step, which was part of a continuum of innovations going back to ancient Greece. As each innovation materialised, a competitive process of selection became active as people made decisions on whether to adopt the new technology. For example, Newcomen's less efficient engine survived the appearance of Watt's engine, and competed with it until the early twentieth century. It is worth also commenting that the relationship between science and technology as exhibited in the steam engine's development was complex. Hero of Alexandria barely used anything that we would call science today. People such as Newcomen and Watt were highly skilled craftsmen-technologists using the work of scientists such as Papin, and doing an enormous amount of both trial and error, and intellectual work to make a working device. The full development of a scientific body of knowledge in heat engines was not produced until 1824 by French mathematician Sadi Carnot, whose theory could be used to maximise the efficiency of any device ("heat engine") that converted heat into mechanical work. Interestingly, his theory assumed that heat was a weightless fluid, which today we would say was wrong. This assumption was adequate and highly fruitful for its time, but has since been shown to be inadequate from our point of view. This hints at the evolutionary structure of science, discussed below in more detail.

3.2.2 Edison and the Electric Light

Thomas A. Edison's project to develop a lighting system began in 1878. At this time in cities across the world gas and electric arc lighting systems had been in use for decades. In 1816 gas streetlights had been installed in Baltimore in the United States. Gas lighting in this form had been developed in England in the 1790s, where oil lamps had been used for street lighting for the preceding century. In the 1780s German pharmacist J. G. Pickel and Belgian physicist Jean-Pierre Minkelers noted that gas could be used for lighting. A hundred years earlier, in 1688, the British Royal Society published an article noting that gas could be extracted from coal and oil, and burned to produce light. Finally, the use of gas as a fuel goes back to China in the 4th century B.C.E., where subterranean gas was extracted and fed through bamboo tubes to provide heat and light. The gas lighting system provided modest amounts of light to homes, shops, hotels, etc., while the arc lighting system produced intense light suitable for streets, factories, ballrooms, theatres, etc. Both systems had their advantages and disadvantages. An extract from Edison's notebooks reads, "to effect exact imitation of all done by gas so as to replace lighting by gas by lighting by electricity ... not to make a large light or a blinding light but a small light having the mildness of gas."[18] Edison's innovation was not simply a light bulb, but a lighting system, including components such as generators, distribution networks, meters, fixtures, switches, fuses, and accessories, many of which were included in the gas lighting system already in existence. Furthermore, Edison made sure that the costs involved in constructing, operating, and maintaining any electric lighting system could compete with gas lighting.

Competition from electric light spurred gas manufacturers to improve their product. They did this by improving the quality of the gas and by using an incandescent mantle (1884). Edison was not the only person developing electric lights; in 1890 Edison, Thomson-Houston and Westinghouse competed in the electric light market, using a variety of patented innovations.

We have shown that the development of the electric light system followed an evolutionary path: it consisted of a series of changes to an existing (gas) lighting system, and was selected by a competitive process.

3.2.3 Osage Orange and Barbed Wire

Archaeologists and historians have found evidence of natural objects that were used directly for various human purposes, including rocks, stones, pebbles, sticks, twigs, branches, leaves, shells, bones, and horns. Details of how some of these items made the transition from natural objects to artifacts have been lost in time, but a recent example that can be detailed is barbed wire. The earliest documentation of wire manufacture is in the Biblical book of Exodus, where gold wire was included in liturgical clothing.[19] Large-scale wire drawing has been practiced since the 15th century. Barbed wire is easily crafted and relies on no advanced scientific knowledge or precise manufacturing process. Yet it did not appear until 1873 in the American Midwest. The impetus came from the westward migration of American farmers from the east coast, who had imported British and European farming practises. These practises included the use of stone or wooden fences, which were readily constructed from local materials along the Atlantic seaboard. As migrating farmers arrived at the western prairies and plains, stone and wood was scarce and expensive, yet they still needed to protect their crops and animals. In this environment, alternative fencing technology was tried, one of which was the European hedgerow. It was found that hedges with thorns were most effective for controlling the movements of cattle. Osage Orange is a short tree native to eastern Texas and southern Arkansas with pronounced thorns that can be planted close and pruned to a thick growth. In 1860 a total of 350 cubic metres of Osage Orange seed were sent to the northern U.S., enough to grow 100,000 km of hedge. But hedges were slow to grow, required pruning, could not be moved, cast shadows on nearby crop area, used much space, and sheltered pests. At the same time, smooth-wire fences had been used in timber-poor areas: they were fast and

[18] *Evolution of Technology*, p. 48, quoting Edison in Harold C. Passer, "The electric light and gas light: innovation and continuity in economic history," *Explorations in Entrepreneurial History* 1, 1949, 2.

[19] Exodus 39:3, 1280-500 B.C.E.

cheap to install and maintain, could be moved easily, cast little shadow on crops, used little space and sheltered no pests. However, cattle frequently broke through them. In 1868 Michael Kelly patented a fence of which he wrote: "My invention [imparts] to fences of wire a character approximating to that of a thorn-hedge."[20] The Kelly fence consisted of sheet-metal thorns fitted to a single strand of wire. In 1874, Joseph F. Glidden patented a two-strand twisted wire holding barbed coils. Jacob Haish, who established a barbed wire factory in competition to Kelly and Glidden, stated: "In the late 60s and early 70s . . . [it] was in my mind . . . to plant Osage Orange seed and when of suitable growth cut and weave it into plain wire and board fences, using the thorns as a safeguard against the encroachment of stock."[21] This case study has shown how a recent technological innovation was based on imitation of a natural object. At the same time the study has highlighted how the failure of existing technologies prompted such an imitation. Wooden or stone fences failed economically because the materials were scarce and expensive, while smooth-wire fences failed functionally because they did not sufficiently control cattle. The solution was a simple combination of the successful traits of two alternatives: smooth wire fences and thorny hedges.

3.2.4 The Cruise Missile

3.2.4.1 Early Development An account of the evolution of the cruise missile up to 1982 has been given by Werrell.[22] In compiling his history Werrel sought to answer, among others, the question, is the cruise missile just another weapon like many others, or does it represent a revolutionary class of weapon? He traces the cruise missile's history back to a 1915 proposal by inventor Peter C. Hewitt to mount a gyroscope in an airframe to produce a flying bomb. This idea was an evolutionary combination of then well established technologies: gyroscopes, airframes and explosives. In 1916 the US Navy trialled an aircraft that flew under autonomous control. The benefits and limitations of the technology were assessed by Lieutenant T. W. Wilkinson, Jr. The benefits were the great moral effect on the enemy, and the difficulty of destroying or diverting autonomous flying bombs. The limitations were their expense, the requirement for complicated launching facilities, and the difficulty of accurate targeting at useful ranges. Subsequent development of the technology was able to maximise the benefits and address the limitations of earlier incarnations, and to do so in a number of applications.

In 1919 the US Army recognised that the "flying bomb will be a great asset to the military forces of the country first perfecting it."[23] In 1921 the US Army let a contract to construct unpiloted aircraft as aerial torpedoes.

Also in 1921 the US Navy experimented with radio to control an anti-aircraft target, but the project died under budget cuts in 1932.[24] In 1935, under a different Chief of

[20] *Evolution of Technology*, p. 53, quoting Jesse S. James, *Early United States barbed wire patents*, Maywood, Illinois, 1966, p. 3.

[21] Ibid., p. 54, quoting Henry D. and Frances T. McCallum, *The Wire That Fenced the West*, Norman, Oklahoma, 1965, p. 23.

[22] Kenneth P. Werrell, *The Evolution of the Cruise Missile*, Air University Press, Maxwell Air Force Base, Alabama, September 1985.

[23] Ibid., p. 21.

[24] Ibid., p. 23.

Naval Operations,[25] the project was revived (the personalities involved in decision-making form a crucial part of the evolutionary environment of an evolutionary system). The project led to an operational target used by the carrier *Ranger* in 1938. Arising from this project was a suggestion to use the technology in combat roles. By this time, two associated technologies had arisen that would make such a role more feasible: airborne television and radar altimetry. In 1937 the Soviets had experimented with television for air reconnaissance, and in 1941 the US Navy successfully tested radar altimeters in a drone.

3.2.4.2 The V-1 Meanwhile in Germany, a pulsejet motor was patented in 1931, which formed the basis of a proposal in 1934 to produce a unpiloted flying bomb,[26] which was produced and demonstrated in 1938. The Luftwaffe cancelled the development of the device because of its insufficient range, low accuracy and high cost. Later in World War II, three environmental factors combined to revive German interest in the technology. First, in 1940 Germany occupied France, thus reducing the range requirement for attacking Great Britain using pilotless aircraft. Secondly, Luftwaffe resources were significantly reduced by 1942, increasing the viability of competing technologies. Thirdly, Britain had begun the strategic bombardment of Germany, goading Hitler to retaliate. In this environment, the Luftwaffe in 1942 gave priority to a proposal to produce an unpiloted flying bomb, approving the development of the V-1 and V-2 missiles at Peenemünde. The V-1s (see figure 13, top) entered operational service on 13 June 1944; by 22 July, 5,000 V-1s had been launched against English targets. The Allies countered using population evacuation, information deception operations, strikes against launch- and supply sites, fighter aircraft specially modified to increase their speed and using special interception tactics, using antiaircraft artillery, and using doctrine developed to coordinate the fighter and gun defences. As a result of these modified defences, during one V-1 attack on the night of 27/28 August 1944, 90 of the 97 observed V-1s were destroyed.[27] Because of the success of Allied defences, the technology of the unpiloted flying bomb was seen as "not worthy of further development, as it is too vulnerable to countermeasures."[28]

3.2.4.3 World War II and Postwar US Air Force Development In May 1942, following the attack on Pearl Harbor (7 December 1941), bureaucratic tensions arose in the US over the use of unpiloted aircraft as assault drones. The Vice Chief of Naval Operations ordered 1,000 television-equipped torpedo carrying drones (TDR-1). But the Chief of the Bureau of Aeronautics resisted, wanting proof that the unpiloted weapon was superior to conventional ones. Later that year efforts to deploy an unpiloted flying bomb from an aircraft were begun. Squabbling continued until 12 July 1944, when 2,500 pounds of salvaged V-1 parts were sent from Britain to the Wright-Patterson Field, and the US Air Force[29] (USAF) ordered the staff there to construct 13 copies of it (see figure 13,

[25] Admiral William V. Pratt was CNO from 17 September 1930 to 30 June 1933, Admiral William H. Standley was CNO from 1 July 1933 till 1 January 1937 (see http://www.history.navy.mil/faqs/faq35-1.htm).

[26] Ibid., p. 41.

[27] Ibid., p. 54.

[28] Ibid., p. 62.

[29] More precisely, the U.S. Army Air Force (the U.S. Air Force did not become a separate department until 1947).

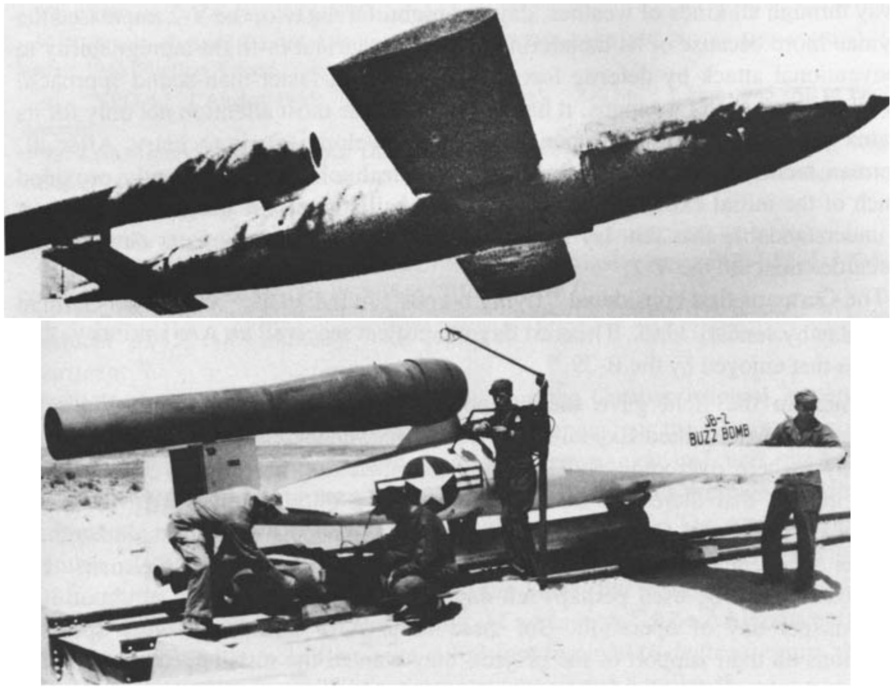

Figure 13: Top: a German V-1 unpiloted flying bomb, an evolutionary ancestor of the cruise missile; bottom: an American copy of the V-1 designated JB-2—a clear case of evolutionary replication

bottom).[30] The US War Department quickly realised that the device's targetting and logistics needed improvement. Nevertheless, by December 1945 the USAF considered the feasibility of a production rate of 1,000 a day.

Further developments in unpiloted flying bombs reflected the same pattern of incremental development, many failures, and some successes, leading to further branching developments. The devices were launched from the ground, from ground vehicles, from submarines, surface ships and aircraft. By mid-1946 the United States was funding 47 distinct guided missile development projects. Even the United States could not afford the resources to continue such diversity, and massive cuts were imposed by the Truman administration in 1947, when the missile budget was cut from \$29 to \$13 million.[31] A vigorous competitive selection process ensued to maintain only those ideas which were seen to be of most potential use. By 1948 the US Air Force had cut the number of their surface-to-surface missile development programs from twelve to four: the BANSHEE, the Northrop Snark, the North American Navaho, and the Martin Matador.

The BANSHEE project used the B-29 bomber as a basis to develop a missile with a range of 1000 miles. The project was cancelled after three years because of "considerable problems".[32]

The Northrop Snark program aimed to develop subsonic and supersonic missiles of

[30]Ibid., p. 63.
[31]Ibid., p. 81.
[32]Ibid., p. 82.

1,500 and 5,000 mile ranges. The experimental program was based on vehicles that could be controlled from a mother ship, and that were recoverable using parachutes and skids. Recovering the vehicles reduced the cost and time for missile development. The Snark used stellar monitoring of inertial guidance, and tail-less vehicles that used elevons on wings with saw-toothed leading edges. Despite guidance and reliability problems, it was acquired by the US Air Force in 1957. It was then scrapped by the Kennedy administration in 1961 because it was seen as of "marginal ... value relative to ballistic missiles."[33]

North American Aviation (a predecessor of Boeing) in 1945 proposed modifying the German V-2 rocket by adding wings, substituting a turbojet/ramjet engine, and coupling it to a booster rocket to give the device an intercontinental range. Under US Air Force sponsorship (the Navaho project), they developed a delta wing vehicle with radio controls and landing gear for recoverable testing. Many prototypes failed at launch. Ten unsuccessful launches were attempted between the first and second successful launches of one version of the vehicle, yet a later version achieved a Mach 3 flight lasting 42 minutes and 24 seconds. The Navaho project was terminated in 1958. Nevertheless, the project produced new materials that could withstand aerodynamic heating, and advances were made in aerodynamics, ramjets and guidance systems. Some of the subsystem technologies developed under Navaho were used in other successful systems. For example, the Hound Dog missile, the nuclear submarine *Nautilus*, and the A3J-1 Vigilante bomber all made use of the inertial navigation system developed under Navaho.[34]

The Martin Matador was developed to respond to a requirement for a tactical 175–500 mile range 600 mph surface-to-surface missile. The project struggled under threat of elimination until 1950, when it was given top priority in response to the outbreak of the Korean war. The device resembled a jet fighter of the time, and tests achieved a 71 percent reliability with an accuracy of 2,700 feet. In 1952 a radar terrain map-matching system (developed separately by Goodyear Aircraft Corporation) was installed in the Matador to extend its range and accuracy. The Matador was put into production in 1954 and entered operational service in the 1st Pilotless Bomber Squadron in 1955. The device lasted until 1969, when Pershing missiles took over the role.

This vignette of the post-war development of the cruise missile in the US Air Force is illustrated in figure 14. The diagram illustrates how the technology of "unpiloted flying bombs" was based on technologies arising early in the twentieth century, namely gyroscopes for navigation, radar, flight, and warheads. The development fits well within an evolutionary framework of replication-with-variation and competitive selection. The replication-with-variation mechanism applied throughout the development, and competitive selection took place both within individual projects, between projects, and between cruise missiles and other competing technologies, such as ballistic missiles. The failures of many branches are inherent to the evolutionary process, and should not be viewed as wastage, especially when aspects of failed systems can be successfully applied to other systems, as was the case of the Navaho guidance system.

[33] Ibid., p. 97.
[34] Ibid., p. 101.

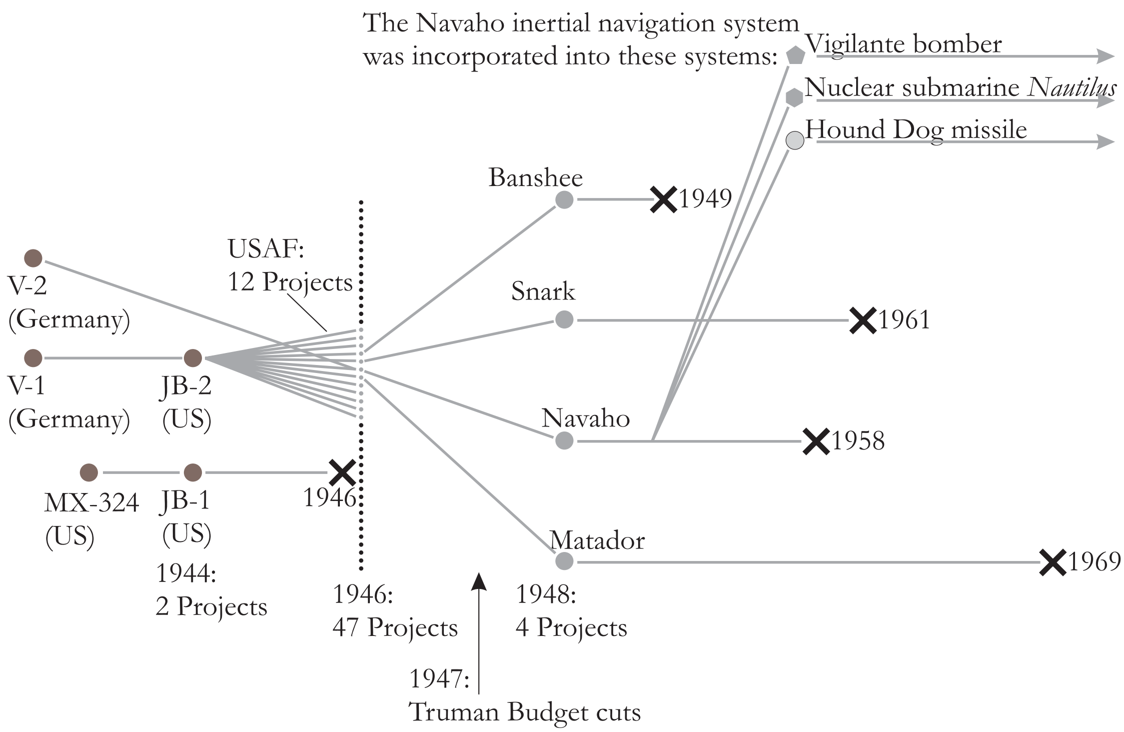

Figure 14: Evolution of the cruise missile by the US Air Force during the post-war period. In 1946 the US Air Force had twelve cruise missile projects. After the Truman cuts of 1947, they reduced this number to four. Some of these were successful, but all had to compete with ballistic missile technology and piloted bombers. Some subsystems of failed projects were successfully incorporated into other systems. The development fits well within an evolutionary framework.

4 Science

4.1 Science and Military Experimentation

In the military domain, there is a trend away from trusting to military judgement alone towards using scientific methods to aid military judgement. Government and financial overseers expect high level military judgements of billion-dollar investment decisions to be supported by an analysis of options that are compared in a scientific way. For example, in an Australian military planning document, experimentation is seen as a key to innovating:[35]

> The adoption of concept-led long range planning and experimentation will inform our way ahead in coming years. ... Through experimentation and simulation, these key future concepts will become more than just words on a page. They will require all of us to overcome organisational inertia, and embrace bold and innovative ways of operating.

"Experimentation" in this context is defined as follows:[36]

> Concept development and experimentation is the application of the structure and methods of experimental science to the challenge of developing future capability. The purpose of this activity is to provide better advice for decision-makers. ... Concept development and experimentation is essential because it helps military innovators to improve and prove their ideas without taking huge risks or outlaying significant resources.

Given this emphasis on using "the structure and methods of experimental science" to develop future military capabilities, we should have a good understanding of that structure and those methods, and how they can be applied to the types of problems that military decision-makers are faced with.

Before we examine the nature of scientific methods, a word about technology:[37]

> We must continue to exploit superior technology to maintain our status as a highly capable defence force. We need to foster a 'technology bias' ... However, we must also remember that our advantage over potential adversaries will not come from technological solutions alone. Our strategic advantage will come from combining technology with people, operational concepts, organisation, training and doctrine.

It is clear that military capability relies on technology to extend human capabilities, and that technology must be accompanied by people to use it appropriately.

[35] *Force 2020*, Australian Defence Doctrine Publication, ADDP–D.2, pp. 1, 25, Canberra, 2002, online at http://defweb.cbr.defence.gov.au/home/documents/adfdocs/mcapstone.htm

[36] *Future Warfighting Concept*, Australian Defence Doctrine Publication, ADDP–D.3, pp. 41, Canberra, 2002, online at http://defweb.cbr.defence.gov.au/home/documents/adfdocs/mcapstone.htm

[37] *Force 2020*, p. 11.

To understand science, we use the work of philosophers who have looked at the way scientists do their work, and who have tried to summarize scientific activities and purposes in a coherent way. Before starting out, we should note that there is still debate in philosophical circles of what science is, and what its value is.

4.2 Scientific Method

The Macquarie dictionary defines science as follows:

> 1.a. the systematic study of humans and their environment based on the deductions and inferences which can be made, and the general laws which can be formulated, from reproducible observations and measurements of events and parameters within the universe. b. the knowledge so obtained. 2. systematised knowledge in general.

This definition tacitly assumes what is called an inductivist view of science, that is, a view of science whereby knowledge is inferred from observation by a process of induction (see below). An alternative is the Merriam-Webster dictionary, which defines science as follows:

> knowledge or a system of knowledge covering general truths or the operation of general laws especially as obtained and tested through scientific method.

This definition is somewhat circular, defining science as system of knowledge arising from something called the scientific method, which it does not define.

To move beyond dictionary definitions, we give a brief summary of the historical development of the philosophy of science.

4.2.1 Naive Inductivism

4.2.1.1 Naive Inductivism Stated Western accounts of the history of the philosophy of science frequently begin with Francis Bacon (1561–1626). Bacon characterised science as a way to improve humanity's earthly condition, and that such improvement would be brought about by collecting and organising facts and deriving theories from them. The facts were to be obtained by use of sensory experience, especially observations of nature; this was in contrast to mediaeval thought, which deduced truth by consulting ancient authorities such as Aristotle or religious texts. Bacon's point was that science consists of general statements about nature (laws, theories, etc.) derived from our experience of nature. Modern examples of scientific statements might be:[38]

From astronomy: Planets move in elliptical orbits around the sun.

From physics: The pressure P of a gas, its volume V, the number N of atoms or molecules comprising the gas, and its temperature T are related according to $PV = NkT$, where k is a constant.

[38] A. F. Chalmers, *What is this Thing Called Science?*, University of Queensland Press, 1982, p. 3.

From psychology: learning is the result of the application of consequences.

From molecular biology ("central dogma"): Expression of the information in genes goes from DNA→ RNA→ protein.

These theories are developed by observing particular planets, gases, animals, or biota, all under certain conditions at particular times, and using certain instruments. Science is seen as a process of generalising, or synthesising, a certain number of a certain type of particular experiences (observations) to universal statements about what will *always* happen in similar situations. The generalising process is called induction, and is the kind of thinking we use when we make the following assertions:

(a) Every time I sat on this chair in the past it has supported me, therefore I am confident that it will always support me when I sit on it.

(b) Every day of everyone's life has begun with a sunrise, therefore the sun will always rise.

(c) Every Swan that anyone has observed has been white, therefore all swans are white.

(d) If a large number of Xs have been observed under a wide variety of conditions, and if all those observed Xs have had the property P, then all Xs have property P.

4.2.1.2 The Merits of Naive Inductivism Naive inductivism gives an account of science that ties in with the popular perception of how scientists go about doing science. It allows for two related and powerful functions of science: prediction and explanation. It does this because the step of generalisation to universal laws can be combined with hypothetical or future conditions to deductively explain or predict what will happen. The general form of such explanations or predictions is:

1. Law or theory.
2. Particular instance fitting within the domain of application of the law or theory.

---

3. Prediction or explanation.

For example, item (a) in the above list of assertions generates a universal law or theory "this chair can support me." Other inductively generated statements of the theory might be made, such as "this chair can support people of about my size and weight", or more succinctly, "this is a good chair". Combined with the hypothetical or future condition of, say, my brother (who is about my size and weight) sitting on the chair, the logical deduction can be made that "the chair will support my brother".

1. Law or theory: this is a good chair.
2. Instance: My brother sits on this chair.

---

3. Prediction: This chair will support my brother.

The structure of the argument is a logical deduction: if (1) and (2) are true then (3) follows by force of logical deduction, but no deduction will establish the truth of (1) or (2): these must be established by induction from observation. There is also an implicit acceptance that the instance (2) is sufficiently close to the domain of application of the theory that the conclusion remains valid. The domain of application of a theory must either be stated as part of the theory or be part of the assumed knowledge of the community. More complex scientific predictions or explanations proceed the same way. Taking the previous physics example:

1. Law or theory: The pressure P of a gas, its volume V, the number N of atoms or molecules comprising the gas, and its temperature T are related according to $PV = NkT$, where k is a constant.
2. Instance: I double the temperature of the gas, keeping the volume constant, and not allowing any gas to enter or escape the container.

---

3. Prediction: The pressure of the gas will double.

In the military domain, we might give an example of an explanation or prediction deducted from an inductively generated theory as follows:

1. Law or theory: Submarines in coastal environments can detect all shipping within 5 km.
2. Instance: I am aboard a submarine in a coastal environment and have detected no shipping.

---

3. Prediction: There is no shipping within 5 km of me.

4.2.1.3 What's Wrong with Induction The inductive step in naive inductivism has no valid foundation. From many observations of white swans, induction tells us that all swans are white. But no logical contradiction is entailed in the simultaneous truth of many observations of white swans, and the existence of black swans. The inductive step:

> If a large number of Xs have been observed under a wide variety of conditions, and if all those observed Xs have had the property P, then all Xs have property P.

is negated by the equally logically possible situation:

> A large number of Xs have been observed under a wide variety of conditions, and all those observed Xs have had the property P, and some Xs do not have property P.

Such a situation is illustrated in figure 15.

Induction cannot be founded on logic, but can it be founded on experience? David Hume (1711–1776) showed that an experiential justification of induction is itself inductive, and hence cannot be used to justify induction.[39] The problem is that no matter how many times induction has been shown to be successful in the past, only induction can be used to conclude that induction will always be successful:

[39] David Hume, *A Treatise of Human Nature*, Book 1, Sect. VI, 1739–1740, online at http://socserv.socsci.mcmaster.ca/∼econ/ugcm/3ll3/hume/treat.html:

> [P]robability is founded on the presumption of a resemblance betwixt those objects, of which

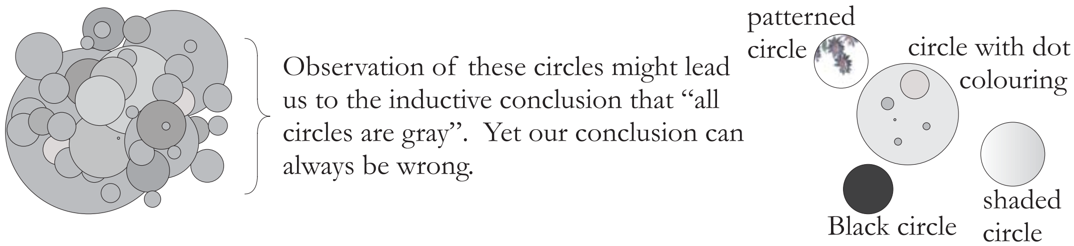

Figure 15: An example of the logically possible counterexample to all inductively generated statements

Induction was used successfully in situation 1.
Induction was used successfully in situation 2.
⋮
Induction was used successfully in situation n.
____
therefore: induction can always be used successfully.

Another problem with naive inductivism is to determine how many observations, and under how wide a variety of circumstances should they be obtained. Clearly one or two observations would be an unpersuasive basis from which to infer a universal theory.[40] Ten million observations might be persuasive, but very expensive. What criteria should we use to determine an appropriate number? There is none. In the same way, nothing in naive inductivism tells us how wide should be the variety under which the observations are made. When investigating the ideal gas law, $PV = NkT$, should we make observations using different shaped containers, different colours, made of different materials, should I have done the experiment under water, in zero gravity, wearing different clothes, etc.? Naive inductivism doesn't tell us: only our theories about what constitutes important experimental factors. Admitting that theories guide our observations takes us beyond naive inductivism, where it is the pure, objective, unbiased observations that give rise to theories.

4.2.1.4 Responses to Naive Induction's Problems A response to the failure of naive inductivism might be to admit that it does not lead to certain knowledge, but that it can nevertheless lead to probable knowledge. However, this approach is susceptible to all of the criticisms given above by simply rewording all conclusions in a probabilistic sense. For example,

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> we have had experience, and those, of which we have had none; and therefore 'tis impossible this presumption can arise from probability. ... We suppose, but are never able to prove, that there must be a resemblance betwixt those objects, of which we have had experience, and those which lie beyond the reach of our discovery.

A detailed analysis of Hume's view of induction is given by Stove (see reference in section 4.2.6).

[40] Even here Chalmers sites the case of nuclear war. Only two observations of the effects of using nuclear weapons in war have ever been made, and yet these are sufficient to infer the theory that nuclear bombs cause massive death, destruction and suffering. Similarly, a small number of observations is enough to tell you that putting your hand in a fire hurts. The old saying "once bitten twice shy" is a statement of strong belief in induction.

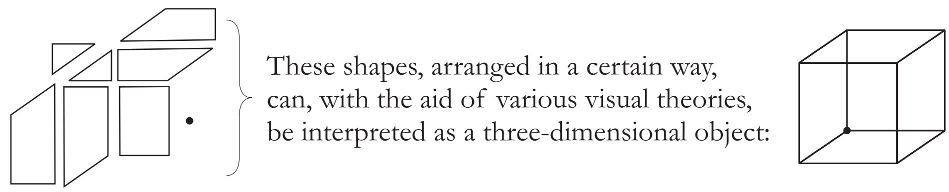


Figure 16: Theory-dependence of vision: the Necker cube

> If a large number of Xs have been observed under a wide variety of conditions, and if all those observed Xs have had the property P, then all Xs probably have property P.

Another response, taken by Hume for example, is to conclude that since induction cannot be rationally justified then science cannot be rationally justified. According to this view, belief in general laws and theories are simply convenient psychological habits.

Some modern scientists hold what might be called the indispensable view of induction, and relate it to the evolution of the mind. According to this view, our minds are structured to believe in induction because the evolutionary process is in a sense a prediction based on past experience. Steven Pinker said:[41]

> we . . . have to make fallible guesses from fragmentary information. [Cognition] solves its unsolvable problem by a leap of faith about how the world works, by making assumptions that are indispensable but indefensible—the only defence being that the assumptions worked well enough in the world of our ancestors.

Pinker argues that our mental organs are designed by a genetic evolutionary process, and those mental organs include a belief in induction because evolution can only work on inductive principles: what worked best in the (recent) past will form a good basis for what will work now. This is not exactly true, of course, because the process of natural selection allows slow genetic change in a slowly changing environment.

4.2.1.5 Theory-dependence of Observation: or Why "Naive" Inductivism? Karl Popper (1902–94) criticised the naive inductivist view that science begins with unbiased observations. This is seen as naive when we recognise that there is no such thing as an unbiased observation. For example, similar observers viewing the same scene under controlled conditions do not necessarily see the same thing. Figure 16 illustrates an example where even a single observer can see different things when viewing a single scene. The dot on the corner can appear at either the front of the cube or the back. Such illusions illustrate the fact that vision is fundamentally an ill-posed problem: patches of light provided to two retinas do not provide sufficient data to give us true three-dimensional information about the objects around us. Instead, a suite of signal processing algorithms and tricks (based on *a priori* theories) carried out unconsciously by the brain provides enough information to us to be sufficiently useful. The interpretation of the various intersecting lines in figure 16 as a cube must rely on a number of image processing algorithms

[41] Steven Pinker, *How the Mind Works*, W. W. Norton & Co. Inc., 1997, p. 30.

in the brain, which are designed to fit parallelograms with certain arrangements of internal lines to pre-existing models of common object types. These algorithms constitute a theory (or *a priori* knowledge) according to which the lines are interpreted as a cube. In this case, the algorithms cannot resolve enough information about the cube to determine its orientation (dot at front or back). In vision as a whole, a large number of image processing algorithms are at work to try to provide us with useful information about size, depth, distance, movement, texture and other characteristics of objects, and many studies have been done showing how the distribution of light falling on the retina is interpreted by the brain in a way that is consistent with theories about plausible normal environments in which the vision system has evolved, not in a way that provides pure truth.[42] Such studies have been done with other senses than vision and produce similar conclusions.

Another illustration of the the naivety of naive inductivism's unbiased observations is that the choice of which things to observe in the first place is a choice guided by pre-existing theories. For example,[43]

> [L]et us imagine Heinrich Hertz, in 1888, performing the electrical experiment that enabled him to produce and detect radio waves for the first time. If he is to be totally unbiased when making his observations, then he will be obliged to record not only the readings on various meters, the presence or absence of sparks at various critical locations in the electrical circuits, the dimensions of the circuit etc. but also the colour of the meters, the dimensions of the laboratory, the state of the weather, the size of his shoes and a whole host of "clearly irrelevant" details, irrelevant, that is, to the kind of theory in which Hertz was interested and which he was testing.

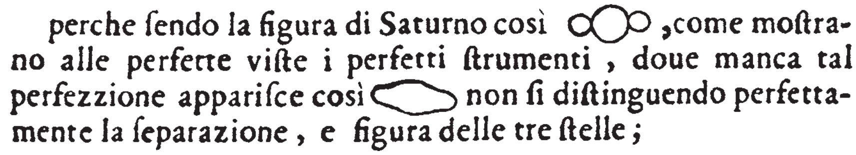
Unless we have a theory to guide us in our selection of important things to observe, then the requirement to be unbiased in our observations would drive us to observe everything: an impossible task. As another example, suppose we have data from intelligence sources in another country. These data might consist of thousands of written reports, photographs, voice recordings, etc. How do we derive useful knowledge from these data? The mere data alone cannot arrange themselves into order of importance. They must be interpreted according to a prior theory. For example, theories of threat might lead us to focus attention on data of a certain kind from certain towns, or pertaining to certain people, etc. And these data, combined with the prior theories, might lead us to think we have a certain amount of knowledge.

4.2.1.6 Problems with Communication of Observation Statements Another aspect of observational experiences is that they must be represented in communicable form, and communicated for public access. (Private, non-repeatable experiences are generally not considered part of science.) There are two problems with this process of representation and communication. (1) Observation statements (for example written sentences) must always be made using theoretical assumptions. For example, the observation statement, "Halving the volume at constant pressure resulted in a halving of the temperature"

[42] For a very readable account and further references, see Steven Pinker, *How the Mind Works*, Chapter 4, p. 211.

[43] Chalmers, p. 33.

assumes a theoretical structure incorporating gases, containers, pressure meters, temperature gauges, etc., as well as a community of people with the necessary education to be able to make use of such theories. (2) Observation statements are representations of experience and are subject to the limitations that distinguish a representation from the reality that it represents. For example, Galileo's observations of the rings of Saturn were reported as follows:[44]


perche ſendo la figura di Saturno così ,come moſtrano alle perfette viſte i perfetti ſtrumenti , doue manca tal perfezzione appariſce così non ſi diſtinguendo perfettamente la ſeparazione , e figura delle tre ſtelle ;

Translated, this is:[45]

> . . . the shape of Saturn is this: , as shown by perfect vision and perfect instruments, but appears thus:  where perfection is lacking, the shape and distinction of the three stars being imperfectly seen.

Limited by the technology of pen and ink, he represented what he saw in the telescope as lines on a page. His observational experience consisted of seeing a certain patch of light through a telescope. Obviously the representation is not the same as the observation.[46] Recognising that representations (or symbols) have limitations allows us to avoid fallacious inferences from symbols to the things they represent. Russell, for example, argues[47] that all symbols in practice are fuzzy: they have a region of applicability having a non-definite boundary, though some symbols may be less fuzzy than others. Science is the process of substituting more precise symbols for less precise ones. According to Russell, the precision of a belief increases as the number of facts that would verify it decreases. Beliefs that are verified by a large number of possible facts are more vague (or fuzzy). He defines a belief as precise when only one fact would verify it, and accurate when it is both precise and true. Russell relates this idea to the problem of resolution in optics, claiming that vagueness of knowledge ("language and thought") is analogous to the vagueness that exists due to the finite resolution of a photograph. His position was that problems of epistemology (or theories of knowledge) are really problems of physics: that the way a meteorologist "knows" about the weather is identical to the way a barometer knows it.

These considerations do not say that observations play no role in science (i.e. the development of knowledge), only that their role cannot be the one given to them by naive inductivism.

[44] Edward R. Tufte, *Envisioning Information*, Graphics Press, Connecticut, 1990, page 120; quoting Galileo Galilei, *Istoria e dimostrazioni intorno alle macchie solari. . .* (History and Demonstrations Concerning Sunspots and their phenomena) Rome, 1613, p. 25.

[45] Drake Stillman, *Discoveries and Opinions of Galileo*, Anchor, 1957, p. 102.

[46] Galileo had a preconceived theory of Saturn whereby he "knew" that Saturn's shape was like three touching "stars", but he interpreted his observation of Saturn's elongated shape as being due to the imperfection of his sensors.

[47] Bertrand Russell, *Vagueness*, Australasian Journal of Psychology and Philosophy, June, 1923, pp. 84–92.

4.2.1.7 Sophisticated Inductivism Only naive inductivists hold the view described as naive inductivism. Some still wish to defend inductivism in a more sophisticated form by admitting that observations are theory-dependent, and that absolute certain knowledge is impossible. For example, some point out that if we assume that induction is false we are led to absurdities such as gathering grapes from thorns or figs from thistles, and hence (by a *reductio ad absurdum*) induction must be true.[48]

Other sophisticated inductivists try to separate (1) the creative process of proposing new theories, and (2) the process of justifying or evaluating theories. The first is admitted to be somewhat mysterious (due to inspiration, genius, happy accident or methodical work), and as yet outside our ability to analyse formally. But sophisticated inductivists claim that we are fully entitled to assess theories as true (or false), or probably true (or false), by gathering facts from observations by induction.

Chalmers[49] questions the legitimacy of separating the creation of theories from the justification of theories because a theory that can itself lead to the creation of a new theory is more justifiable than one that only accounts for existing observations. Creation and justification of theories are therefore related and not clearly in separate realms. He argues that "it is essential to understand science as a historically evolving body of knowledge and that a theory can only be adequately appraised if due attention is paid to its historical context." He also highlights the remaining difficulty that observations are theory-laden, hence fallible; whereas sophisticated inductivists still try to distinguish between the observations on which theories are founded and the theories themselves. The extreme version of this distinction was held by logical positivists, who held that theories could only have *meaning* to the extent to which they were verified by observation.

4.2.2 Naive Falsificationism

Karl Popper is commonly cited as the originator of falsificationism. He described[50] science as proceeding by falsification. Falsificationists admit that theory plays a role in observation, and dispense with claims that observations can prove theories. Scientific knowledge is seen as always tentative and conjectural. New theories are proposed by whatever means they can be to overcome the problems of previous theories. New theories are then subjected to experiment: their predictions and explanations are compared with observations. If theoretical predictions match observations the theory is allowed to remain as useful, though we can never say that it is "true", no matter how many confirming instances we observe; we simply say that it is the best theory we currently have. On the other hand, if theoretical predictions do not match an observation (and only one falsifying observation is necessary to falsify a theory), then the theory can definitely be called false, and is to be rejected. Further new theories must then be developed to account for the

[48] Nicholas Dykes, *Debunking Popper, a Critique of Karl Popper's Critical Rationalism*, Philosophical Notes, No. 65, Libertarian Alliance, 2003, online at http://www.libertarian.co.uk/lapubs/philn/-philn065.htm. The same author also justifies induction based on something he calls the Law of Identity, and claims that, in fact, all knowledge is acquired inductively.

[49] p. 35.

[50] Karl R. Popper, *The Logic of Scientific Discovery*, Hutchinson of London, 1959: translation of *Logik der Forschung*, Vienna, 1934.

observations that falsified the old theory. Science is seen as a process of trial and error, or learning from mistakes.

If the purpose of science is to produce descriptions of the world that are universally applicable, then by logical necessity, one (genuinely) falsifying instance is indeed sufficient to falsify a theory. The scientific theory that all swans are white is falsified by the single observation of a black swan. The scientific theory that $PV = NkT$ would be falsified by an observation of a gas whose pressure within a vessel of constant volume remained constant when heated.

4.2.2.1 Examples of Non-Falsifiable Statements According to the falsificationist view, only falsifiable theories are admitted as candidates into science. Unfalsifiable claims are not candidates for science. These are examples of statements that are not falsifiable:

1. *Being aggressive will not bring results this year.*[51]

   This is a horoscope that is not specific enough in its predictions to be falsified: it does not specify the degree of aggression, nor the kind of results brought about by various kinds of aggression, nor the time period that might elapse between the aggression and any result of it.

2. *The equation $x^n + y^n = z^n$ has no non-zero integer solutions for x, y and z when $n > 2$.*

   This is known as Fermat's last theorem,[52] and is generally held to have been proven. It is therefore not falsifiable because it is a consequence of the definitions of the relevant mathematical entities, relations and operations; no contrary observation is possible according to the conventions of mathematics. If we take unfalsifiable statements to be outside the domain of science, then proven theorems of mathematics must lie outside the domain of science.

3. *[F]riction ... is everywhere in contact with chance, and brings about effects that cannot be measured.*[53]

   This statement is unfalsifiable because no observation could refute it: it claims the existence of unmeasurable effects, therefore no observation can refute it. (The first part of the statement might be falsifiable if we could observe an instance of "friction" not "in contact with chance", but it is unclear what exactly this means.

4.2.2.2 Examples of Falsifiable Statements In contrast, the following would be falsifiable statements, and are therefore scientific statements:

1. *It never rains on Wednesdays.*

   This theory would be falsified by the observation of rain on a Wednesday.

[51] www.horoscope.com

[52] http://www-gap.dcs.st-and.ac.uk/∼history/HistTopics/Fermat's_last_theorem.html.

[53] Carl von Clausewitz, *On War*, ed. and trans. Michael Howard and Peter Paret, Princeton, N.J., Princeton University Press, 1976, p. 89.

2. *All matter is made up of atoms.*

   This theory would be falsified by the observation of matter that was not made up of atoms.

3. *A constant force applied to a body will result in a constant acceleration.*

   This statement is a result of Newton's laws of motion and was thought to be valid for two hundred years. This statement would be falsified by the observation of a body that did not undergo constant acceleration under the action of a constant force.

Statements (1), (2) and (3) are falsifiable and false. Rain does fall on Wednesdays, there are forms of matter not made up of atoms (the plasma or neutron state matter in stars for example), and matter moving at speeds near the speed of light do not accelerate at a constant rate under the action of a constant force. Strict falsificationists would demand the rejection of all such falsified theories from science.

4. *People evolved a desire to engage in war because natural selection favours traits that, on average, increase reproductive success.*[54]

   This theory would be falsified if it could be shown that average reproductive success would not have been increased by engaging in warfare scenarios appropriate to our evolutionary ancestors. This has been shown for females, whose chances of successful reproduction are generally not limited by the number of available males, so falsifying this theory for women, and possibly also explaining why in general women never evolved a tendency to band together and raid neighbouring villages for husbands. The theory still may be true for males, thus explaining why males evolved a tendency to band together and raid neighbouring villages for wives.[55]

5. *Mammals evolved during the Cenozoic era.*

   This theory would be falsified by the observation of a precenozoic mammalian fossil.[56]

6. *Vaccination protects against disease.*

   Popper used this example to illustrate that applying the falsifiability criterion is not always simple. He states:[57]

   > [The] theory that vaccination protects against smallpox is falsifiable: if someone who has really been vaccinated still gets smallpox, the theory is falsified. This example may also be used to show that the falsifiability criterion has problems of its own. If one out of a million vaccinated people

[54] Steven Pinker, *How the Mind Works*, p. 514.

[55] Tooby, J. and Cosmides, L., *The Evolution of War and its Cognitive Foundations*, Annual Meeting of the Human Behaviour and Evolution Society, Ann Arbor, Mich. Institute for Evolutionary Studies Technical Report 88–1, University of California, Santa Barbara, 1988; Tooby, J. and Cosmides, L., *Cognitive Adaptations for Threat, Cooperation and War* Plenary Address, Annual Meeting of the Human Behaviour and Evolution Society, Binghamton, New York, August, 1993; Keely, L. H., *War Before Civilization: The Myth of the Peaceful Savage*, New York, Oxford University Press.

[56] This example is inspired by a remark attributed to J. B. S. Haldane that evolution would be falsified by the discovery of a precambrian rabbit.

[57] Karl Popper, *The Logic and Evolution of Scientific Theory*, 1972 in *All Life is Problem Solving*, Routledge, London, 1999, p. 17.

> gets smallpox, we will hardly consider our theory to be falsified. Rather, we will assume that something was wrong with the vaccination or with the vaccine material. And in principle such an escape route is always possible. When we are faced with a falsification, we can always talk our way out somehow or other; we can introduce an auxiliary hypothesis and reject the falsification. We can '*immunize*' our theories against all possible falsification ... Yet the falsifiability criterion does have its value. It is applicable to the theory of smallpox vaccination ... If the proportion of vaccinated people who get smallpox is roughly the same as (or perhaps even greater than) the proportion of unvaccinated people who get smallpox, then all scientists will give up the theory of vaccine protection.

7. *Focusing on strategic lockout can play a key role to enable a warfighting force to achieve a rapid termination of hostilities.*[58]

   The theory is of the form "if p, therefore q", where p is the strategic outlook focus and q is rapid termination of hostilities. The theory is falsified if "if p, therefore q" is false, namely p is true and q is false. Assuming that the terms within this statement are well defined, the statement would be falsified if an operation was carried out that focussed on strategic lockout, yet termination of hostilities was not rapid. Defenders of the hypothesis might point out that it is stated "p *can* enable q" and use this fact to dismiss such an apparent falsification. Such apparent robustness to falsification tells us that we should state our hypotheses as clearly as possible. Stating merely that a thing "can" or "may" or "might" be a consequence of an action blurs the causal connection between them, making it immune to falsification, but also making it immune to being classed as genuine (scientific) knowledge. Clear hypothetical statements allow us to analyse them to determine how they can be falsified (or even confirmed), and perhaps to cast them as logical propositions for subsequent analysis.

8. *Regime X has weapons of mass destruction.*

   This would be falsified by an observation that regime X has no weapons of mass destruction. However, observing the absence of a thing has inherent difficulties, and requires an exhaustive search. For example, "this haystack contains no needles" can only be established by an exhaustive search of the haystack. Establishing that regime X has no weapons of mass destruction requires some kind of exhaustive search of regime X. The regime of Saddam Hussein claimed that it had no weapons of mass destruction: a difficult claim to prove because of the exhaustive knowledge criteria; along the lines of proving that your haystack contains no needles.

9. *Regime X has no weapons of mass destruction.*

   This would be falsified by an observation that regime X has at least one weapon of mass destruction. US Secretary of State Colin Powell attempted to falsify this theory as it applied to the regime of Saddam Hussein.[59]

[58] David S. Alberts, John J. Garstka and Frederick P. Stein, *Network Centric Warfare: Developing and Leveraging Information Superiority*, CCRP Publication Series, 1999, p. 165.

[59] Colin L. Powell, *Remarks to the United Nations Security Council*, New York City, February 5, 2003.

4.2.3 Problems with Falsification

4.2.3.1 Fallible Falsifiers A major problem with the view that science proceeds strictly by falsification is that falsifying observation statements are not infallible.[60] As shown in section 4.2.1.5 on page 29, observation cannot be completely separated from theory, and all observations are made according to a theory of what is important. Therefore "if a theory clashes with some observation statement, it may be the observation statement that is at fault."[61] For example, the moon is observed to be larger when it is near the horizon, yet we do not use that observation to falsify the standard theory of the moon's orbit, which holds that it size should not vary by the amount observed. Such near-horizon observations of the moon are generally dismissed as optical illusions, even though the mechanism of the illusion is not well understood.

Popper was aware of this problem, and concluded that the empirical basis of science was therefore not absolute, but a matter of community satisfaction. However he apparently did not accept that fallible falsifying observations undermined the notion of conclusive falsification.

4.2.3.2 Practical Complexities When attempting to falsify a theory there may arise many practical issues that muddy the waters. The relevant theory must be interpreted and used correctly to produce an adequate prediction of what should be observed in a given experimental situation. That situation must indeed be established during the experiment, and the appropriate observations must be made using proper instruments in the proper way. Such observations may need to be further analysed and processed to generate results that can be compared with the theory. If an incompatibility is then discovered between the experimental result and the theory, it may well be that the theory is yet valid, and that something has gone amiss with the rest of this complex process of experimentation. Theories can always be protected from potentially falsifying observations by introducing supplementary theories. A theory will come unstuck only when such supplementary theories become ridiculous, or lacking in "beauty", compared to a competing theory. Judgements of supplemental ridiculousness or lack of beauty are typically made by a complex social process.

An example of a protected theory was Aristotle's (384–322 B.C.E.) moon theory, which held that, being a heavenly body, the moon was perfect, eternally unchanging and without corruption.[62] The features visible to the naked eye needed some explanation, lest the theory be falsified *prima facie*. Aristotle recognised this problem, and postulated that the moon was subject to some of earth's sublunary corruption. A competing theory was proposed by Plutarch (46–120 C.E.), who suggested that the moon's features were due to the shadows of rivers or chasms. An explanation that became standard in medieval times, when Aristotle's influence was very great, was that the moon, while still being a perfect sphere, had regions of different density, and these gave rise to its mottled appearance. Telescopic observations of the moon by Thomas Harriot and by Galileo (working independently in 1609–1610), clearly showed mountains and valleys casting shadows that changed in length with the illumination of the surface, and that therefore the moon was not a

[60] Chalmers, p. 60.
[61] Ibid., p. 61.
[62] http://galileo.rice.edu/sci/observations/moon.html

perfect sphere. Most astronomers, and most of the Jesuit fathers in Rome, were conviced at this point that the moon's surface was rough. A last-ditch attempt at protecting Aristotle's theory was proposed by Christoph Clavius (74 years old), who was quoted in an April 1611 letter to Cardinal Bellarmine, head of the Jesuit College in Rome, written by the College mathematicians: "But it appears to Father Clavius more probable that the surface is not uneven, but rather that the lunar body is not of uniform density and has denser and rarer parts, as are the ordinary spots seen with the natural sight."

4.2.3.3 History of Science The history of science shows that many of the great theories of their day would have been rejected by strict falsificationists because there were observations that were in apparent contradiction to them. Chalmers[63] cites the following examples. (1) Newton's theory of gravitation: falsified by observations of the moon and the planet mercury. (2) Bohr's theory of the atom: falsified by observations of stable matter, despite the prediction of Bohr's theory that orbiting electrons would collapse into the nucleus in timescales of about 10^{-8} seconds. (3) Maxwell's kinetic theory of gases: falsified by measurements of specific heats of gases. (4) Copernicus's theory that the earth rotates around the sun: falsified by the observation that loose objects on the earth are not flung off the earth, as they would be flung off any other rotating object.

4.2.4 Paradigm Shifts

Although induction and falsification seem to capture some aspects of activities that most people would call scientific, neither view provides a secure logical foundation for certain knowledge, and both fail to capture major aspects of progress in science. The history of scientific development shows us that in the early stage, the fundamental concepts used within a theory, the theory itself, and the applicable experimental techniques and methods begin by being ill-formed in the sense that they may be vague, and even contradictory in some sense, yet may still be seen as offering a better alternative than some older, inadequate theoretical structure.[64] Chalmers discusses the difficulty of establishing clear concepts in a new field, and thereby legitimises vagueness and imprecision, at least during the early stages of a field's development:[65]

> The dependence of the meaning of concepts on the structure of the theory in which they occur, and the dependence of the precision of the former on the precision and degree of coherence of the latter, can be made more plausible by noting the limitations of some alternative ways in which a concept might be thought to acquire meaning. One such alternative is the view that concepts acquire their meaning by way of a definition. Definitions must be rejected as a fundamental procedure for establishing meanings. Concepts can only be defined in terms of other concepts, the meanings of which are given. If the meanings of these latter concepts are themselves established by definition, it is clear that an infinite regress will result unless the meanings of some terms are known by some other means. A dictionary is useless unless one already knows

[63] Ibid., p. 66.
[64] Ibid., p. 78.
[65] Ibid.

> the meanings of many words. Newton could not define mass or force in terms of pre-Newtonian concepts. It was necessary for him to transcend the terms of the old conceptual system by developing a new one. A second alternative is the suggestion that the meaning of concepts is established through observation, by way of ostensive definition. ... [But one] will not arrive at the concept "mass" through observation alone, however closely one scrutinizes colliding billiard-balls, weights on springs, orbiting planets, etc., nor is it possible to teach others the meaning of mass merely by pointing to such events. It is not irrelevant to recall here that if one attempts to teach a dog by way of ostensive definition, it invariably responds by sniffing one's finger.

The ideas in this quotation seem to me to at least partly explain limitations to the perfection of knowledge, and to provide a hint at how theories first arise. Initial vagueness and incoherence is permissible in the early stages of a theory. A theory arises and begins to develop by analogies, metaphors, thought-experiments, gut-feelings, or whatever. Motivation to develop theories can also arise from many sources: accidental observations, new applications of technology or community rivalry. As researchers become more familiar with the theory, its concepts, and the relationships between these and observational experiences, a valid theory will become more precise, more internally consistent and more consistent with other relevant theories observations. As a new theory matures it becomes more internally consistent and capable of precise predictions; experimental techniques will become more refined and the role of new concepts arising within the theory will become clearer. Chalmers cites[66] the cases of Galilean mechanics, atomism, and especially the electric field as examples of theories in which concepts arose as vague and ill-formed, and over periods of time, sometimes centuries, these concepts became more precise and coherent.

Chalmers reviews[67] the work of Lakatos (1922–1974) and of Kuhn (1922–1996) who characterised science as proceeding by (1) competition between competing research programs, or (2) revolutionary paradigms, respectively. Both accepted the problem of theory-laden observation (like Popper) but highlighted the fact that much scientific activity did not consist in vigorous efforts at falsification. There was a place for accepting fundamental assumptions and getting on with making esoteric predictions and looking for confirmations within a theoretical system, or "paradigm". In Kuhn's view, major points of scientific progress are marked by the revolutionary overthrow of old paradigms with new ones, as anomalies gradually become evident.

Neither Lakatos nor Kuhn gave accounts of scientific development that could guide scientists in their work, in contrast to Popper whose articulation of the principle of falsifiability can indeed provide some practical guidance. Neither did Lakatos or Kuhn provide clear criteria for distinguishing science from non-science, again in contrast to Popper, whose falsifiability criterion is used for such a purpose.

Nevertheless Lakatos and Kuhn did describe aspects of science that are important, such as the fact that psychological and sociological factors operating within the surrounding culture and within the scientific community play a role in how theories are assessed. For example, a theory may be seen as neater, or simpler, or more plausible, and therefore

[66] Ibid., pp. 78–79.
[67] Ibid., Chapters 7–8.

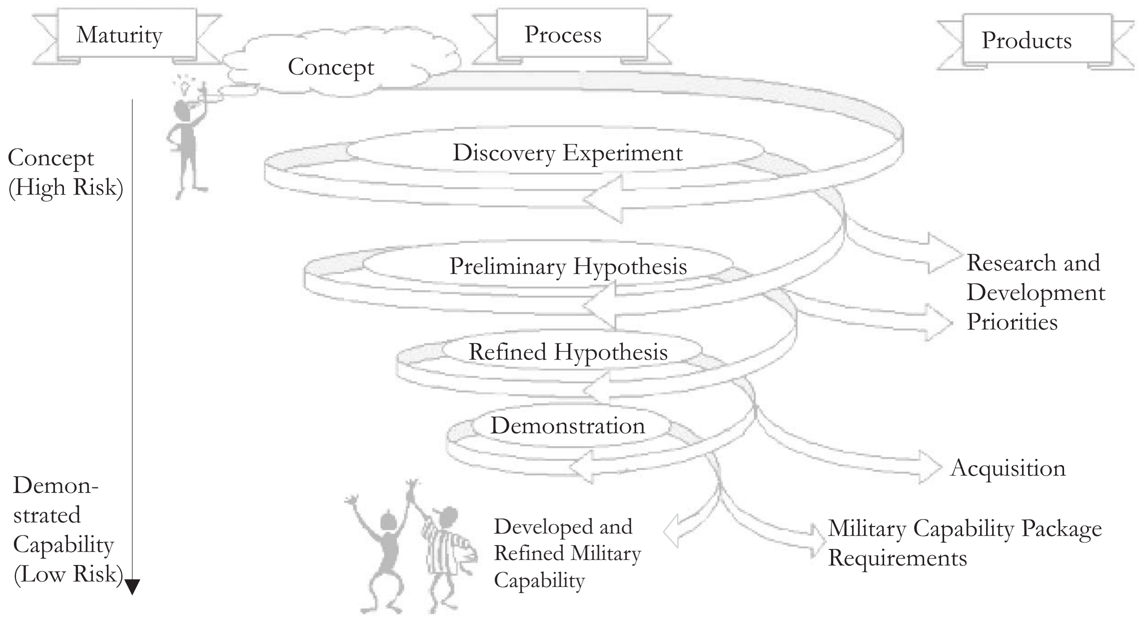


Figure 17: One view of the military experimentation process (adapted from Alberts and Hayes, p. 26)

accepted over a rival theory on what are basically aesthetic grounds. An extreme characterization of such psychological or sociological effects might be to label them as mob-psychology, truth by power, jumping on the bandwagon, the buzzword effect, etc. Some have taken such a position to its limit, resulting in postmodern deconstructionism,[68] a position in which, according to Chomsky "we are reduced to primal screams".[69] For Chomsky, consistency and responsibility to fact remain as essential for rational enquiry. He freely assumes the legitimacy of rational enquiry, rather than justifying it on some other basis.

Finally we note that much military guidance on experimentation as an innovation technique focusses on either induction or falsification. For example, Alberts and Hayes suggest using many observations to increase confidence in results.[70] They propose an innovation model that uses a gradually maturing experimental program involving initial "discovery" experiments (involving vague concepts) that generate more testable hypotheses for subsequent falsification.[71] They view this process as a diminishing spiral homing in on a developed and refined military capability (see figure 17).

[68]Jacques Derrida is widely considered the originator of deconstruction. The relationship of deconstruction to science is briefly described and critiqued at http://en.wikipedia.org/wiki/Deconstruction.

[69]Noam Chomsky, *Rationality/Science*, Z Papers Special Issue, 1995(?), online at http://www.-zmag.org/chomsky/articles/95-science.html

[70]David S. Alberts and Richard E. Hayes, *Code of Best Practice for Experimentation*, CCRP Publication Series, July, 2002, p. 81, online at http://www.dodccrp.org/Publications/zip/COBPE.exe

[71]Ibid., p. 26.

4.2.5 Science Has No Method

Paul Feyerabend (1924–1994) began as a follower of Popper but later came to the view that there were serious problems with all attempts to unify science under a single set of rules, such as "inductivism" or "falsificationism". His work has provoked sharp responses, and there is on-going debate about how to interpret him. I will let him speak for himself for a while:[72]

> The thesis is: *the events, procedures and results that constitute the sciences have no common structure*; there are no elements that occur in every scientific investigation but are missing elsewhere. Concrete developments (such as the overthrow of steady state cosmologies and the discovery of the structure of DNA) have distinct features and we can often explain why and how these features led to success. But not every discovery can be accounted for in the same manner, and procedures that paid off in the past may create havoc when imposed on the future. Successful research does not obey general standards; it relies now on one trick, now on another; the moves that advance it and the standards that define what counts as an advance are not always known to the movers. Far-reaching changes of outlook, such as the so-called 'Copernican Revolution' or the 'Darwinian Revolution', affect different areas of research in different ways and receive different impulses from them. A theory of science that devises standards and structural elements for *all* scientific activities and authorizes them by reference to 'Reason' or 'Rationality' may impress outsiders—but it is much too crude an instrument for the people on the spot, that is, for scientists facing some concrete research problem.

He believed that no set of rules yet proposed stood up to historical scrutiny of the way scientific knowledge has developed. Furthermore, he also came to object to the attempt to restrict science to such a set of rules. He saw science as requiring a certain freedom of method, and restricting it to a single orthodoxy could result in the shackling of scientific creativity within restrictive ideological or even quasi-religious bonds. This position is summarised in his oft-quoted phrase: "The only principle that does not inhibit progress is: anything goes."[73] Some people—from deconstructionists to defenders of more traditional views of science—have interpreted Feyerabend as being an anti-rationalist, and of equating science with voodoo or astrology. But he still seemed to claim, or perhaps assume, a special place for science's success in prediction and technology:[74]

> ... Feyerabend took umbrage at this misunderstanding and mis-use of his work: "How can an enterprise [science] depend on culture in so many ways, and yet produce such solid results? ... fly-by-night mystics, prophets of a New Age, and relativists of all sorts—get aroused by the cultural component and forget predictions and technology."

[72] Paul Feyerabend, *Against Method*, Introduction to the Chinese Edition, Verso Books, 3rd edition, 1993, p. 1, italics in original.

[73] Ibid., p. 14 (1975).

[74] http://www.wikipedia.org/wiki/Paul_Feyerabend. Internal quotation is from Paul Feyerabend, *Atoms and Consciousness*, in *Common Knowledge*, Vol. 1, No. 1, 1992, pp. 28-32.

Chalmers critiques Feyerabend's ideas mainly on the ground that they are somewhat utopian: scientists find themselves in an objective social situation and are not free to adopt *any* method available. To advocate Feyerabend's anarchistic view within such a situation means that those in power hang on to it, and nothing changes.

4.2.6 A Defence of Rationalism

David Stove has questioned[75] the whole enterprise of philosophers of science such as Popper, Kuhn, Lakatos, and Feyerabend. His critique begins with the assertion that:[76]

> Much more is known now than was known fifty years ago, and much more was known then than in 1580. So there has been a great accumulation or growth of knowledge in the last four hundred years.

This he calls fact (A), and proceeds to show how Popper, Kuhn, Lakatos and Feyerabend write in such a way as to deny (A), or at least to make (A) seem less plausible. Stove argues that their writing accomplishes this goal in two ways: (1) by neutralising success words, and (2) by sabotaging logical expressions. A common technique identified by Stove for achieving this neutralising and sabotaging is by extensive use of scare-quotation marks. For example, the statement "Cook discovered Cook Strait" can be neutralised by saying "Cook 'discovered' Cook Strait". Stove goes on to illustrate how Popper's, Kuhn's, Lakatos's and Feyerabend's accounts of science are irrationalist, and searches for the key premise of their irrationalism. This key premise is, according to Stove, inductive scepticism. Stove presents a highly technical analysis—occupying most of the second half of his book—of Hume's argument for scepticism about induction.[77] Stove identifies a missing premise in this argument and characterises people who share a belief in this missing premise as "deductivists". Deductivists, according to Stove, have a standard of reasonable argument that:[78]

> demands that, if P is to be a reason to believe Q, then Q is *deducible* either from P itself, or from P along with such limited additional premises as can be themselves part of a reason to believe Q.

Stove states that few people are deductivists, and that most people hold to the validity of non-deductive logic, or confirmation theory, or what Stove, quoting Carnap, calls 'inductive' logic. He argues that deductivism and inductive fallibilism are independent, but that Popper, Kuhn, Lakatos, and Feyerabend conflated the two:[79]

> Arguments from the observed to the unobserved really are incurably invalid: *this* much of Hume's philosophy of science is true, and in this much all empiricists are now agreed. But, this much being agreed, any empiricist who is

[75]David Stove, *Scientific Irrationalism, Origins of a Postmodern Cult*, Transaction Publishers, New Jersey, 2001.

[76]Ibid. p. 21.

[77]Ibid. pp. 111–160, online at http://www.geocities.com/ResearchTriangle/Facility/4118/dcs/hume/hume.html

[78]Ibid. p. 150 (emphasis in original).

[79]Ibid. p. 169 (emphasis in original).

> also a *deductivist*, as all our authors [Popper, Kuhn, Lakatos, and Feyerabend] are, condemns himself, not just to irrationalism, but to unseriousness, about science.

This leads to a confused state of mind, in which logical truths (necessary truths) seem to affect beliefs in a way that they have no right to:[80]

> A contemporary philosopher [i.e. one with deductivist leanings], will admit [that] it is a mere *logical* truth that tomorrow's flames *may* be unlike past ones; and that therefore this *cannot* be a reason to *doubt* that they will be like them. Yet in spite of all his efforts to prevent it doing so, this logical truth operates on his mind as though it *were* such a reason, and a weighty one ... [T]his state of mind is a confused one.

Stove, with approval, restates scientific belief as analogous to believing, on the basis that I hold 999 of 1000 tickets in a fair lottery to be drawn tomorrow, that while it is possible that I will not win a lottery tomorrow, it is probable that I will.

4.3 The Limits of Knowledge

At the close of the nineteenth century humanity's knowledge was seen as almost perfect. Some, taking inspiration from Laplace (1749–1827) thought that knowledge of the positions of every piece of matter and the forces acting on them was sufficient to determine the exact state of the universe at any future moment. This view was based on the success of Newtonian mechanics and came to be called scientific determinism.[81] During the twentieth century this view was shown to be false by three separate developments: Heisenberg's uncertainty principle, Gödel's theorem and chaos theory.[82] Since we are discussing the role of science in the generation of knowledge, it is appropriate to comment briefly on these fundamental limits to what we can possibly know.

4.3.1 Heisenberg's Uncertainty Principle

In 1927 Werner Heisenberg published an article explaining that the precision to which the position and momentum of a particle can be determined is strictly limited. More specifically, the uncertainty in position is inversely proportional to the uncertainty in momentum:

$$\Delta x \Delta p \geq \frac{h}{4\pi}, \tag{1}$$

where Δx is the standard deviation in position measurement, Δp is the standard deviation in momentum measurement, and h is Planck's constant. The value of Planck's constant is small ($h = 6.6 \times 10^{-34}$ J s), limiting the effect to atomic scales.

The uncertainty principle expresses the limit to which objects can be thought of as well-defined particles, emphasising the fact that particles are not exact mathematical points or

[80] Ibid. p. 193 (emphasis in original).

[81] Stephen Hawking, *The Universe in a Nutshell*, Bantam Books, 2001, p. 104.

[82] Ibid., p. 139.

spheres but exhibit wave-like properties. The limit has been confirmed by many experiments. Heisenberg pointed out that the principle set limits on causal determinism: since particles had inherently uncertain positions and momenta, an exact future state could not be determined. Instead we can only determine the probability distribution of future states.

The uncertainty principle is important at atomic scales, and is used to understand the properties of electronic components, metals, lasers, and chemicals. Yet, according to the American Institute of Physics, it "does not say 'everything is uncertain.' Rather, it tells us very exactly where the limits of uncertainty lie when we make measurements of sub-atomic events."[83]

4.3.2 Gödel's Theorem

A proven fact of mathematics (Gödel's incompleteness theorems) is that any sufficiently strong formal mathematical system can give rise to a statement that can be neither proven nor disproven within that system. Gödel's theorems laid to rest the idea that formal mathematical systems could prove all mathematical truths. The broader implications of this mathematical fact is the subject of debate,[84] and has been taken by some to imply the formal impossibility of complete rational knowledge:[85]

> Gödel's incompleteness theorems philosophically state that rational thought cannot find the total ultimate truth. The complete truth is inaccessible even in principle, no matter how large the brain, no matter how long one has to cogitate.

Such conclusions implicitly identify "rational thought" and "truth" with the kinds of operations possible within the "formal axiomatic systems" used by Gödel. Roger Penrose has used an argument based on Gödel's theorem to suggest[86] that there is a non-algorithmic element to human thinking that can never be duplicated by a machine.

The theoretical physicist Stephen Hawking, who describes himself as a Popperian positivist,[87] simply points out that Gödel's theorem came as a "shock to the scientific community" because it overthrew the previous rosy views of mathematics.[88] He says that it forms part of a core set of limitations to scientific knowledge. In a separate essay, Hawking applies Gödel's theorem to science by pointing out that we and our scientific models exist as part of the universe that the models purport to describe, and that this self-reference means that Gödel's theorem can be applied to science; therefore science is either inconsistent or

[83] http://www.aip.org/history/heisenberg/p08c.htm

[84] For an extensive discussion of Gödel's theorem and its implications see Douglas R. Hofstadter, *Gödel, Escher, Bach: An Eternal Golden Braid*, Basic Books, 1999.

[85] Darryn J. Reid and Ralph E. Griffin, *A Woven Web of Guesses: Canto Three: Network Centric Warfare and the Virtuous Revolution*, 8th International Command and Control Research & Technology Symposium, National Defense University, Washington, DC, June, 2003.

[86] Roger Penrose, *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics*, Oxford University Press, 1989, and *Shadows of the Mind: A Search for the Missing Science of Consciousness*, Oxford University Press, Oxford, 1994.

[87] Hawking, *The Universe in a Nutshell*, p. 31.

[88] Ibid., p. 139.

incomplete (present theories are both).[89] Hawking does not expect the development of an ultimate science formulated as a finite number of principles.

Other thinkers minimise the applicability of Gödel's theorem. They point out, for example, that human thought is far from being like a formal axiomatic system; humans can be mistaken about mathematics and they can change their minds.[90] Minsky argues that people rarely think using formal logic.[91] Steven Pinker[92] highlights the fact that people are much better at solving puzzles cast as social contracts than they are at solving strictly logical ones, even when identical principles of logic are at issue, and that therefore minds are not formal logic machines. Pinker points out that theories arising from Gödelian considerations have proven scientifically sterile, and have failed to explain or inspire any discoveries about how the mind works.[93]

Gödel's theorem is used by some to conclude that "absolute truth is not achievable"[94] Yet in mathematics there do exist truths that are absolute (proven theorems). The question of whether mathematics is a purely mental construct or exists in the external world is a source of numerous debates.[95] Hence it is unclear whether proven mathematical theorems lie within the strict Popperian limits of science, therefore we should be cautious about using Gödel's theorem to draw scientific conclusions. This caution should be further emphasised because of the difficulties of scientific method, in particular on the theory-dependence of observation and the problems with induction highlighted above. There is no such thing as certain scientific truth, and all scientific statements must be taken with at least a grain of tentativeness. Again, Pinker points out that "our minds are not pipelines to the truth. Our minds evolved by natural selection to solve problems that were life-and-death matters to our ancestors."[96] The brain has certain limitations because of that; for example, we cannot hold ten thousand words in short-term memory, or mentally rotate an object in four dimensions. Pinker uses these considerations, rather than Gödelian considerations, to put limits on the explanatory capabilities of human thought.

4.3.3 Chaos Theory

The third limit to scientific determinism comes from chaos theory. An inherent property of many dynamical systems is that their motion is so complex and sensitive that the motion appears to be random. Such systems are said to be chaotic. Even systems that conform to exact deterministic laws (like Newton's) exhibit chaotic properties. An

[89] Stephen Hawking, *Gödel and the End of Physics*, lecture at the Centre for Mathematical Sciences, Cambridge, July 2002, online at http://www.damtp.cam.ac.uk/strtst/dirac/hawking/

[90] Marvin Minsky, *Conscious Machines*, published in "Machinery of Consciousness", Proceedings, National Research Council of Canada, 75th Anniversary Symposium on Science in Society, June 1991, online at http://kuoi.asui.uidaho.edu/∼kamikaze/documents/minsky.html, see also Daniel Dennett, *Review of Penrose, The Emperor's New Mind*, The Times Literary Supplement, September 29-October 5, 1989, online at http://ase.tufts.edu/cogstud/papers/penrose.htm.

[91] Ibid.

[92] Steven Pinker, *How the Mind Works*, p. 336, using a test devised by psychologist Peter Wason.

[93] Ibid., p. 97.

[94] Reid and Griffin, *Canto Three*.

[95] The contribution of a reviewer is acknowledged on this point.

[96] Steven Pinker, *How the Mind Works*, p. 561.

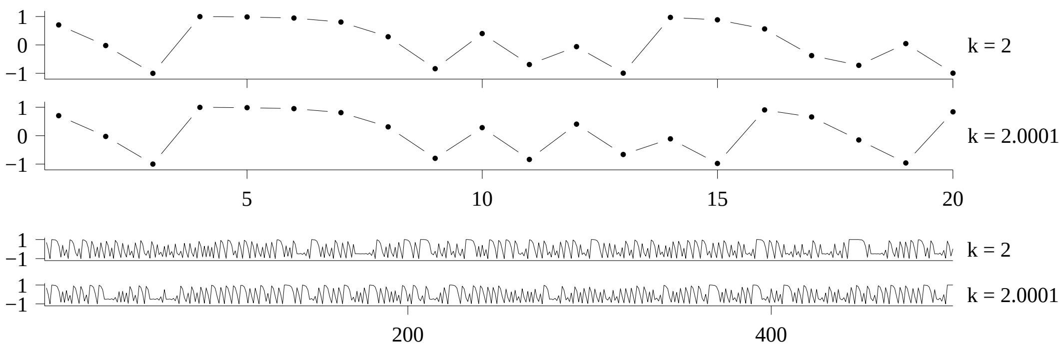


Figure 18: An example of a chaotic system

example[97] is shown in figure 18, which shows iterations of the formula

$$x_n = kx_{n-1}^2 - 1. \tag{2}$$

The plots show results for $k = 2$ and $k = 2.0001$; and an initial value $x_1 = 0.7$. Until about the 11th iteration the two systems are similar, but thereafter the values become completely different; the difference arising only from the tiny variation of the k-value in the formula. Furthermore, there is no way of predicting what the value of x will be for a given n other than calculating out the entire series: the values could be anywhere between -1 and 1, and no periodic simplification applies. The lack of any periodicity is illustrated by the lower two plots, which show the first 500 iterations of both systems.

Ian Stewart makes a case that the scientific quest for simple laws that describe regular features of nature has left out most of the reality of nature, which is chaotic. He cites the case of the motion of the planets as an example. Whereas early investigations of planetary motions revealed "laws" whereby planets moved in perfect ellipses around the sun, the reality is that all planetary orbits are chaotic.[98] In the solar system, chaos affects mainly the inner planets; for example, the eccentricity of the orbit of Mars will change by a maximum of about 20 percent "bringing it close to the orbit of the Earth with the danger of collision."[99] These changes may take place over a timescale of about 5 billion years. In this particular example, the chaotic effect may seem small (or at least, slow) but Stewart offers many examples where chaos theory has been used to solve many practical problems: extracting conversations from recordings made in a noisy room, fractal image compression, providing advice to investment banks on market movements, analysing train wheel wear, improving dishwashing machines by making their arms move chaotically, reducing the energy required for interplanetary space probes, information encryption, and controlling the quality of spring wire.[100]

Chaotic behaviour limits predictability in many ways, while offering explanations of many features of nature that simpler (linear) theories cannot. Experimentation must

[97]Ian Stewart, *Does God Play Dice—The New Mathematics of Chaos*, Blackwell Publishers, second edition, 1997, p. 14.

[98]Ibid., p.246–9.

[99]Ibid., p.248.

[100]Ibid., p.297.

be designed appropriately for chaotic systems. In chaotic systems, even a deterministic prediction can be non-repeatable (because of the extreme sensitivity to unobservable variables). Experiments must aim to measure features of the system that are repeatable (using different brands of equipment, for example).

Related to chaos theory is complexity theory, and the phenomenon of emergent properties. In chaos theory, simple rules applied to simple systems can lead to complex phenomena; in complexity theory, complex interactions between large numbers of elements can lead to simple "emergent" phenomena.

In the military context, it is interesting to note that complexity theory seems to explain some features of evolutionary (competitive) systems, in particular how complex systems have a tendency to position themselves near the boundary between simple behaviour and chaotic behaviour (the "edge of chaos"):[101]

> the suggestion is that selection or learning drives them [complex adaptive systems] towards this boundary. Systems that are too simple do not survive in a competitive environment, because more sophisticated systems can outwit them by exploiting their regularities. ... Systems that are too random also do not survive, because they never achieve anything coherent. ... So it pays, in survival terms, to be as complicated as possible, *without* becoming totally structureless. Evolutionary systems are forced to poise themselves on the edge of chaos.

5 Evolutionary Model of Science

In the previous sections we reviewed some ideas from the past 400 years of what science is, and why successive generations have thought that the ideas of previous generations cannot be quite right. Now I want to rebuild a picture of science using the evolutionary model of innovation. Much of this section is inspired by Popper's evolutionary epistemology.[102] I will apply the evolutionary model to science at two levels: at one level, we will build a picture of science as an evolutionary method of refining competing theories using experimentation as a survival test; at another level, we will see how philosophies of science have developed historically according to evolutionary principles. In the next section we will draw on these lessons about how science does and does not work, and apply them to the processes of military experimentation.

5.1 Inductivism as Evolutionarily Justifiable

Popper admitted that knowledge is mostly *a priori*. When we observe something, we must have a pre-existing framework, or theory into which the observation somehow "fits".

[101] Ibid., p. 370, see also Paulo Murilo Castro de Oliveira, "Why Do Evolutionary Systems Stick to the Edge of Chaos?" *Theory in Biosciences*, 120(1) 2001.

[102] Karl Popper, *The Logic and Evolution of Scientific Theory*, 1972, *The Epistemological Position of Evolutionary Epistemology*, 1986, *Towards and Evolutionary Theory of Knowledge*, 1989, *All Life is Problem Solving*, 1991, in *All Life is Problem Solving*, Routledge, London, 1999.

Popper's question was: "where does this pre-existing framework come from?" His answer was that living things (biological replicators) structurally anticipate the environment that they will live in. For example, eyes are a genetic anticipation that an organism will live in an environment of light: the light will be useful for survival and reproduction. The structure of the eye can be thought of as a kind of knowledge about how the world will be, based on the organism's historical experience of evolutionary trial and error. The organism's genes are an encoding of that history. But eyes by themselves are worse than useless: they cost a lot of energy to produce, weaken the mechanical strength of the skull, etc. In addition to eyes, the organism needs an ability to process the signals provided by the eyes, and that ability constitutes another kind of knowledge about how the world will be, based on the past experience of evolutionary trial and error.

A reliance on inductively generated knowledge is thought by psychologists to originate in humans' evolutionary past, and the utility of inferring on the basis of categorisation. Steven Pinker[103] argues that concepts like "rabbit" or "mammal", or "fish" are useful because they mesh with the way the world really works. Properties like, "having long ears", "being suckled", and "having fins and scales" are not distributed evenly among the world's objects, but tend to run in groups. The groups that we recognise are generally those useful for making inferences about the world's objects. "Redness" is a useful concept if your survival depends on eating ripe fruit. Inference is a useful behaviour if the world is filled with things that have family resemblances. "I ate something with long ears and a cottontail yesterday, and it tasted fine, so from now on, rabbit is on the menu." "I ate a green apple yesterday and I felt sick, so from now on, green apples are off the menu." This is the type of success that gives induction or inference its utility, and it relies not on logical foundations of certainty but on estimates of reliability that conferred adaptive advantages over evolutionary time.

Richard Dawkins has introduced the idea of the extended phenotype:[104]

> [The] phenotype [is] the manifested attributes of an organism, the joint product of its genes and their environment during ontogeny. A gene may be said to have phenotypic expression in, say, eye colour. ... the concept of phenotype is *extended* to include functionally important consequences of gene differences, outside the bodies in which the genes sit.

For example, beavers' dams can be seen as a product of the natural selection of beaver genes, just as much as beavers' tails, or teeth are.[105] Using this idea, we can view human products—technology, science, culture, language, etc.—as a product of the phenotypic expression of human genes, just like the human skeleton, or the human brain. Is this a useful view? Part of the utility lies in the opening it provides to investigate creative processes. Non-evolutionary explanations of the weaver bird's nest might have attributed its nest-building behaviour to instinct—a crude explanation at best. An evolutionary explanation would view such creative innovation in much the same vein as innovation in bodily structures. New structures emerge as an accumulation of successful moves through

[103]Pinker, *How the Mind Works*, p. 306.

[104]Richard Dawkins, *The Extended Phenotype*, Oxford University Press, 1982, p. 292 (emphasis in original).

[105]Ibid., p. 200.

a feasible design space. These moves can be changes in bodily structures, or behaviours, or cognitive activity, this in turn can result in nests, dams, teeth, missiles or scientific theories.

5.2 Falsification and Evolving Memes

Can science be seen as a cognitive activity that is governed by evolutionary principles? We can check using Gould's three characteristics of evolutionary systems (see p. 2):

1. *First, that all organisms produce more offspring than can possibly survive.* The "organisms" here are scientific theories competing for resources (research funding, experimental opportunities, etc.) Not all can survive in their environment of limited resources. Furthermore, people tend to isolate a single "best" theory for propagation, leaving the rest to wither.

2. *Second, that all organisms within a species vary, one from the other.* At any point in history there can be a diversity of scientific theories, seeking to explain the same phenomena by various devices. For example, is light a wave or a particle? Is the nucleus more like a bag or a liquid drop? Is empty space best described as a vacuum, an aether, or a quantum foam? This situation applies at the forefront of science, before a contending theory has gained dominance. Within the forefront of science, "conventional" science can be seen as a non-varying successful explanation of a particular phenomenon; we can view it in our evolutionary model as a steady-state replicating explanation that will survive until some new observation forces it to be updated or abandoned. Science textbooks describe this body of ideas.

3. *that at least some of this variation is inherited by offspring.* "inheritance" occurs when a scientific theory is communicated. The communication can occur "sideways" as people talk to each other about their ideas, or "vertically" as new-comers to a particular area learn the ideas passed on from their elders.

In section 4.2.1.7 (page 32) we noted Chalmers' view that:

> [It] is essential to understand science as an historically evolving body of knowledge and that a theory can only be adequately appraised if due attention is paid to its historical context. Theory appraisal is intimately linked with the circumstances under which a theory first makes its appearance.

Chalmers recognises both the dependence of scientific development on the environment, or "historical context" as he put it here, as well as the competitive process taking place between rival theories. But if science evolves, what is it that either changes or endures through the replication process? Dawkins has proposed an analogous concept to the gene to denote the unit of replication in cultural evolution, called the meme.[106] We can consider science as constituting part of the more general "memosphere" of ideas transmitted from person to person and generation to generation. The memosphere is the total set of memes, or mental replicators, vying for attention and survival in human culture.

[106] Richard Dawkins, *The Selfish Gene*, Oxford Press, 1976, Ch. 11.

The evolutionary survival test for scientific theories is the empirical process—an experimental test of the conformity of the theory with the world of publically sensed, repeatable, and communicable experience (observation). If the theory is falsified it may become extinct; if the theory is validated it may survive in the memosphere of science. Theories can have offspring that resemble their parents, but with variation. Theories that are verified survive unchanged; theories that are falsified can be modified so that they conform with the new observation. The modifications arise from human creative processes: analogies, metaphors, thought-experiments, gut-feelings, or whatever. Old theories can be rearranged, augmented by other theories, or parts can be removed. New generations of theories are submitted to further survival tests.

To apply evolutionary ideas to science (or technology) does not say that human reason and intention are discounted as explanations of what goes on. Rather it gives another layer of explanation that may serve to clarify features that remain mysterious from other viewpoints. Explanations of innovation that rely on qualities such as "genius" or that use words such as "revolution" will generally not be fruitful for further innovation. Human reasoning processes (neuroscience and psychology) have been studied within an evolutionary framework for the past forty years, and evolutionary ideas have been successful in explaining many phenomena.[107] Some cognitive scientists have proposed evolutionary accounts of human creativity. For example, when comparing the mechanisms operating when Garry Kasparov and Deep Blue created good chess moves, Daniel Dennett argues that both these thinkers—man and machine—must use "an outstanding array of heuristic pruning techniques", and that both Kasparov and Deep Blue benefitted from an initial endowment of successful strategies; pre-programmed in Deep Blue's case, and learned from past experience with other players, from coaches and from books in Kasparov's case.[108] Dennett uses other examples and considerations to conclude that "genius itself is a product of natural selection and involves generate-and-test procedures all the way down."[109] At the same time, Dennett argues, it is not necessarily always best to view genius in this light. There are other levels in which a more folklore-ish view of genius is appropriate: "it is often no longer particularly perspicuous to view it [genius] solely as a cascade of generate-and-test processes. It often makes good sense to [think] of the agent as a self, with a variety of projects, goals, presuppositions, hopes, ... In short, it often makes good sense to adopt the intentional stance towards the whole complex product of evolutionary processes."[110]

Support for an evolutionary theory of creativity also comes from artificial intelligence research. For example, computerised models of human creative thought processes have been described by Hofstadter,[111] who believes that "pattern perception, extrapolation, and generalization are the true crux of creativity"—a view that reflects the inductivist aspect of science. Hofstadter goes on to argue for an evolutionary view of the origin of such creativity: "evolution . . . saw to it that we were constructed in such a manner that

[107] See Steven Pinker, *How the Mind Works* for an overview.

[108] Daniel Dennett, *Could there be a Darwinian Account of Human Creativity?* in Andrés Moya and Enrique Font (Eds.) *Evolution: From Molecules to Ecosystems* Oxford University Press, 2004, online at http://ase.tufts.edu/cogstud/papers/valencia.htm

[109] Ibid.

[110] Ibid.

[111] Douglas R. Hofstadter, *Fluid Concepts & Creative Analogies: Computer Models of the Fundamental Mechanisms of Thought*, Basic Books, 1996.

quick filters do work. Of all that is out there to potentially explore, only a small percentage attracts us, allowing us to discount most claims to our attention. We pay little attention to most ads, most books, most people, most music, most radio and television shows, most countries—in short, to most things in the world. We cannot possibly explore everything in depth, and luckily, we do not need to in order to do well in life."[112] This radical filtering of attention-grabbers ties in nicely with the theory-ladenness of observations in science (see sections 4.2.1.7 and 4.2.4 on pages 32 and 38, respectively). Evolutionary processes have endowed humans with a cognitive mechanism for drawing analogies while filtering out the infinite amount of cognitive dross that there is to potentially explore; and this mechanism is what is called theory-laden observation.

We can combine the ideas of memetic evolution and the extended phenotype as descriptions, respectively, of scientific and technological evolution. Memetic evolution differs from genetic evolution in that genetic evolution views change as taking place for the "benefit" of the gene. Genetic changes are counted as successful if they build structures (bodies, behaviours) that increase the probability of producing viable offspring, thereby propagating the (new) gene. Memetic changes are counted as successful if they build structures (theories, symbols, cultures) that increase the probability of producing viable offspring, thereby propagating the (new) meme.

6 Military Experimentation

According to the Australian Navy Innovation Strategy, the innovation process centres around the following activities: technical demonstrations, simulations, studies, wargames, exercises, and international cooperation.

We describe these as the tools of experimentation, and can be seen as providing a military equivalent to experimental activities in science. In the following section we describe each of these activities, and their strengths and limitations for innovation. We have added some other tools to the list, namely historical studies, actual operations and discovery experiments, since these can also generate information useful for innovation.

I will point out how each activity can be seen as fitting into the evolutionary model of innovation.

6.1 Technical Demonstrations

In a technical demonstration, a specific technology is shown to its potential military users. The goal of the demonstration can be to simply expose a new technology in a "technology fair" setting so that people can begin to think about its potential benefits. Or the goal might be to give operators access to a new technology so they can compare it to an existing system. Or the goal might be to "socialise" an idea, and get feedback from people who might use the technology on how, when and where it might be usefully employed.

[112]Ibid., p. 108.

A demonstration can take place at any stage in the evolutionary maturity of an innovation. In the early stage, ideas may be vague. At later stages, an idea or technology may be demonstrated after a research program has already been completed. Ideas may be firm, and the demonstration would have more of an educational or publicity role. Information gathered during a demonstration, if any, would comprise feedback on perceived benefits or limitations.

From a scientific standpoint, a demonstration would be independent of an experiment. Specifically, a demonstration would not involve specific observations, measurement, data gathering, data processing or verification or falsification of hypotheses, at least in any formal sense. These activities may be carried out informally, for example, by asking the audience of a demonstration what they thought about it.

The cost of a technical demonstration is generally low. They are usually carried out under controlled conditions.

6.2 Scientific Studies

Scientific studies include operations research and operations analysis. These can be prompted by innovations in technology or in how technologies are employed, and can be used to inform the research community or military innovators. Often, the aim of scientific studies is to generate quantitative information about alternative future systems for people who must decide which alternative to buy. Such studies can use existing or newly developed theories, which can be based on mathematical models, to compare technologies or means of employment against one or more metrics. It may be that a process of historical or experimental study must be done to develop these theories or models. Such models are often probabilistic.

The metrics generated by scientific studies can be divided into measures of effectiveness (MOEs) or measures of performance (MOPs). A measure of effectiveness is an aggregated measure of the outcome of an activity using an entire system, and a measure of performance is a discrete measure of a separate event occurring within a subsystem. Measures are determined using mathematical models of subsystem performance and of the interactions between subsystems within the overall system. Validation of the models and measures is either by community consensus or by comparison with historical data. Opposition modelling, if any, is usually “passive”; the opposition is modelled from an “own” viewpoint and is usually done in a pre-programmed way (if we do X, then they will do Y). Scientific studies can range in scale from little more than “back of the envelope” calculations to work extending over years. Control of variables and reproducibility of results are high.

6.3 Simulated Operations

Simulated operations involve replacement of all or part of a real operation by a model, usually a software model. Sometimes actual operational software is used in an artificial environment to generate output from some kind of artificial input, or stimulation. The abstracted software is sometimes referred to as a *virtual* representation of the system.

Human interactions with the virtual system are often a target of study in simulated operations. The human interaction can range from a single operator evaluating a display, to a simulated battle between teams of human opponents. Using opposing teams of humans can give information about systems or behaviour in a competitive environment.

6.4 Wargames

The philosopher Ludwig Wittgenstein (1889–1951) pointed out that there is no fixed concept of a game; there is no definition of "game" that includes things we normally call games (card games, board games, computer games, Olympic games) and that leaves out things that we don't normally call games (fortune-telling, sitting on a company board, surfing the internet, fighting a war).[113] If this is the case for games in general, then it is probably true for wargames as well. Yet some authors still try to be precise. For example, Peter Perla dismisses the 1979 Webster's New Collegiate Dictionary definition of a wargame:[114]

> a simulated battle or campaign to test military concepts and uses. Conducted in conferences by officers acting as the opposing staffs [or] a two-sided umpired training maneuver with actual elements of the armed forces participating.

Perla criticises these definitions as imprecise and misleading. He says they lead military professionals to look to wargames to solve problems that they cannot usefully address. Instead, Perla offers this definition of a wargame:

> a warfare model or simulation whose operation does not involve the activities of actual military forces, and whose sequence of events affect and is, in turn, affected by the decisions made by players representing the opposing sides.[115]

Perla wants to rule out specific things from wargaming. In priority order, the following are not to be seen (according to Perla) as aspects of wargames:

1. analysis (i.e. wargames do not produce a rigorous, quantitative or logical dissection of a problem, nor do they define precise measures of effectiveness for comparing alternative solutions);
2. reality (wargames are abstracted from real-life experience);
3. reproducibility (wargames cannot be replayed changing only the outcomes of the die rolls).

Given these restrictions, do wargames produce *any* worthwhile information? If rigour, logic, reality and reproducibility are not to be expected of wargames, then it seems fair to conclude that they produce no scientific information. Despite the discussion above on

[113] Ludwig Wittgenstein, *Philosophical Investigations*, 1953.

[114] Peter P. Perla, *The Art of Wargaming, A Guide for Professionals and Hobbyists*, Naval Institute Press, Annapolis, Maryland, 1990, p. 164.

[115] Ibid.

various problems of scientific method, it would be a stretch to include a non-reproducible, non-analytic, experience as part of science.

So what does wargaming do for us? Perla states:

> In the end, a wargame is an exercise in human interaction, and the interplay of human decisions and the simulated outcomes of those decisions makes it impossible for two games to be the same. As a result of all those factors, wargaming is not a panacea for learning about or solving the problems of warfare. Its forte is the exploration of the role and potential effects of human decisions; other tools are better suited to the investigation of other more technical aspects of reality.[116]

Perla seems to view wargames as chaotic systems, with information about human decisions being the primary output. Being chaotic does not rule wargames out of an evolutionary understanding of the process of experimental innovation, since we have seen a specific case above (see section 2.2.3 on p. 8) where the evolutionary model led to a chaotic system. His view is that wargames are an exploratory device for raising issues:

> The role of wargames ... is to help human beings investigate the processes of combat. ... Wargame designers, players, and analysts, as well as critics and decision makers who judge the validity of a game or define its results only in terms of what happened, not why, or only in terms of "lessons learned" not "issues raised," have lost sight of what a war-game really is and where its main benefits are to be found. Wargames can help explore questions of strategy, human decision making, and war-fighting trends. They are of little use in providing rigorous, quantitative measures to "objectively" prove or disprove technical or tactical theories. Instead, they can often provide the kernel of new theories that can be tested with other tools.

Perhaps we can propose a new definition of a wargame:

> The competitive pitting of human intellects in a simulation of war.

In our evolutionary model of scientific theory development, wargames would fit in at the pre-theoretical stage. Before a firm theory has developed, a wargame might serve to highlight the need for a new theory and might point out the "landscape" into which a new, emerging, theory should fit. Human decisions and interactions would form the main features of this landscape. A wargame could be used to explore the effect of new technologies or employment concepts on human decision making. Given the primacy of human decisions in wargaming, it would be important to maximise the information gathered concerning player decisions, and to employ psychological or cognitive techniques to explore the issues impacting these decisions.

Perla states that the following elements are essential to a wargame: objectives, a scenario, a data base, models, rules, players, and especially analysis. This last item contradicts his earlier statement that wargames are not analytical activities (or, if they are, then only in broad terms, and not in precise, quantitative terms).

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[116]Ibid.

Wargames focus on broad questions of human interaction. Control and reproducibility are low, but the competitive motivation of the players can yield information about what might be important factors to consider in a given scenario. Development of a scenario in which military systems compete is a strong feature of wargames, and corresponds to specification of the competitive environment in the evolutionary innovation framework. Wargaming can reflect the evolutionary mechanism of replication-with-variation by having players use orders of battle (ORBATs) which are identical (and generally similar to contemporary ones) except for a single aspect. For example a joint operational game might use two ORBATs, with and without some new proposed technology (platform or representative capability) to see what operational effects it has. The feedback from the players on "what worked and what didn't work, and why" can constitute part of an evolutionary survival test for a new idea.

6.5 Military Exercises

A military exercise can be used to trial a real system in a realistic environment. This is done at a later stage in the evolutionary maturity of a concept, because a detailed idea of how it is to be used and how it is to be integrated into the rest of the warfighting system must already be formed. Military exercises can involve a simulated component, where the simulation might be a computerised model of the new concept that is able to interact with other real subsystems withing the overall warfighting system (an example is the US Navy's Fleet Battle Experiments).

Military exercises may be very costly because they typically require the use of military systems and personnel, as well as civilian researchers. A military exercise is generally a very multi-faceted activity because of competing demands made on exercise resources. An entire exercise is a non-repeatable activity, though repeated subsystem measures may be practical, depending on the degree to which the system under test is able to be isolated. The advantages of testing a concept in an exercise are the operational realism and the validity of the scenario.

6.6 International Cooperation

International cooperation can be applied across the range of military experimentation activities: technical demonstrations, scientific studies, simulations, wargames, etc., can all be done by international groups. In our evolutionary model of innovation, international cooperation can be seen as a way of increasing the diversity of the ideas testing, and of increasing the resources available for carrying out the test. Other countries face similar challenges in defence innovation. They may have done their own investigations of competing ideas, and may be able to suggest new ideas to the broader international defence community. International cooperation can be a way of sharing information among countries with similar interests so that the research cost is shared.

The advantages of international cooperation must be weighed against the extra administrative cost. Overseas travel is usually required to establish the cooperation, and long timescales are often required to achieve results because communication among the participants is more difficult, even using email and video teleconferencing. Another counterbalance to international cooperation is the problem of goal sharing. Countries may have slightly different requirements during an agreed cooperative project which adds to the complexity of achieving mutually beneficial outcomes.

6.7 Military Innovation Toolbox

The previous section gave a view of some of the experimentation tools that can be used for military innovation. The tools are not mutually exclusive. For example, a simulated operation can be linked to an exercise—ships at sea, for example—to exploit the advantages of each. International cooperation can be used across the entire range of experimentation activities, including actual operations. A wargame can use the results of scientific studies or can generate issues for new scientific studies, or both. Such interactions are natural in our evolutionary model of innovation because ideas tested using one method can be tested again—possibly with variation—using another method. (Such interaction between different experimentation techniques are hinted at, perhaps in a more mechanistic way, in figure 17 on page 39.) An idea that shows its worth in more than one method of testing increases the credibility of the idea, and is analogous to biological structures that provide advantage in many environments (for example armour plating of an animal gives it an advantage against many predators).

The range of experimentation tools aim to innovate the military during peacetime (see also figure 22 on page 58). The ultimate evolutionary test for military ideas, though, is actual war, or other operations such as peacekeeping, emergency response, etc. Ideas that are successful in actual operations will generally be kept for subsequent operations in a similar situation. (If the situation is not sufficiently similar, it leads to the observation that military structures are always optimised for the last war, not the present one.)

Despite the fact that actual warfare can be seen as the ultimate evolutionary test, the problem from a scientific viewpoint is that warfare is neither reproducible nor controlled. Myriad interactions take place, and the presence of an intelligent and adaptable enemy tends to confuse the cause and effect linkages that scientific thought tries to isolate. For such reasons, the scientific credibility of judgements based on actual operations is diminished for scientists.

At the other end of the spectrum, a demonstration of a new system in a controlled laboratory-style environment is the most credible activity from a scientific perspective. The system under investigation can be isolated, and variables affecting its behaviour can be controlled, leading to a clear identification of cause and effect. But from a military point of view, such an activity may be seen as interesting but not decisive: military thinkers may wonder what the tactical or operational implications of the system might be, whether it will perform the same way in a hostile environment, and so on. For such reasons, the military credibility of controlled technical demonstrations is diminished for military thinkers.

We summarise the credibility problem in figure 19. On this diagram we show the various tools that can be employed to assist in military innovation along the horizontal

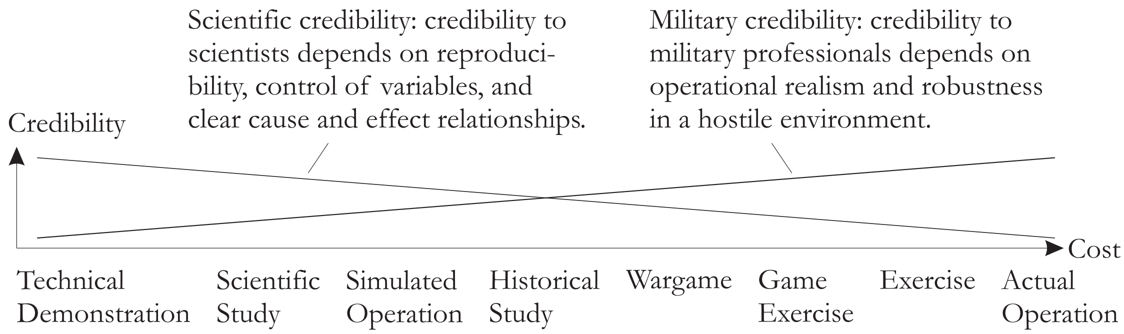

Figure 19: Credibility of various innovation activities to different communities

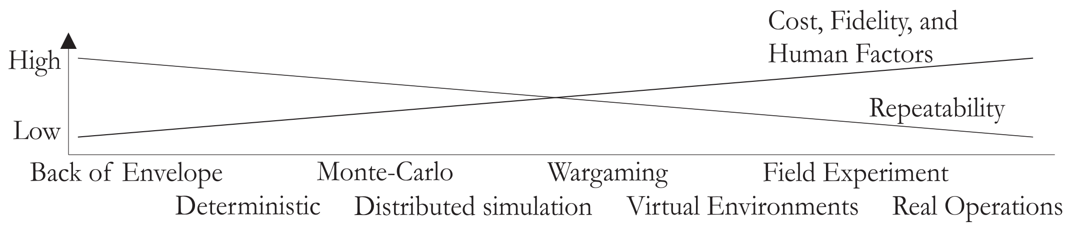

Figure 20: An analysis of experimentation and research methods, adapted from Hazen et al. *(see text)*

axis, arranged in approximate order of increasing cost. A subjective measure of credibility forms the vertical axis. The exact positioning of the innovation tools along the horizontal axis can be debated, and would depend on the scale of the particular activity. Historical studies are included because from an evolutionary point of view, it is important to understand why systems have worked in the past. The credibility measure forms part of the evolutionary fitness that determines the survival of a new concept. The credibility of the means used to present a concept—the experimentation venue—(the horizontal scale in figure 19) will have an impact on the concept's success, depending on the community of people making up the decision making body. Experimentation activities near the centre of the diagram, where the credibility of the outcome is medium but about the same for the two communities should form a good method of achieving common ground between the military and scientific communities.

Hazen, *et al.* (see figure 20) have offered a model of what they called operations research (OR) models and tools.[117] In their model they have ranked a set of modelling techniques in order of increasing cost, fidelity, human factors (the amount of human interaction in the modelled system), and of decreasing repeatability. By comparing figures 19 and 20 we can see how the OR models and tools map to the innovation activities and how the factors of fidelity and repeatability contribute to the overall credibility of an activity's output. I have not attempted to analyse the human involvement in the various innovation activities summarised in figure 19; human activity can be high or low for each activity, depending

[117]M. G. Hazen, L. Booth, C. Davis, D. Gamble and T. Mansell, *The Place of Virtual Environments in a Layered Approach to OR analysis: A Naval Perspective*, in the Proceedings of the Australian Society For Operations Research, September 2001.

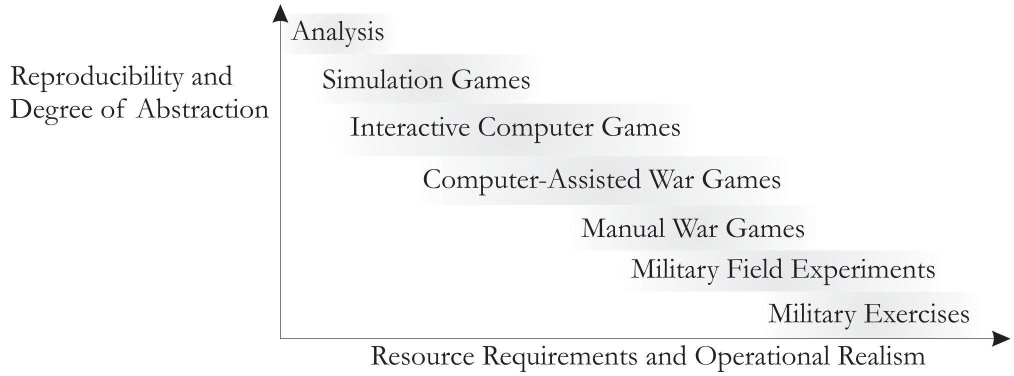

Figure 21: A proposed view of "game" activities ("Analysis" is identified with "Analytic Games" in the original)

on the concept under test. For example, if an autonomous platform is tested in actual operations the human activity would be low. If a situation awareness and decision making aid is tested using a concept demonstrator the human activity would be high.

Perla (see figure 21) presents an analysis of what he calls "game" activities.[118] These activities range across the spectrum of what here we call military experimentation, and the figure highlights the inverse relationship between (1) the resource requirements and operational realism on the one hand, and (2) reproducibility and degree of abstraction on the other. These relationships are very similar to those shown in figure 20, and affect the credibility of the various activities that we have proposed in figure 19.

The spectrum of military experimentation activities, besides being seen as offering a range of methods, measures and credibility, can also be seen as reducing the generation time associated with evolutionary testing (see figure 22). The top diagram in the figure represents a hypothetical situation in which innovation is done by replacing existing major capabilities with new, possibly slightly different, major capabilities. The major capability replacement time is seen as being possibly much longer than the time taken for the environment to change. Within this situation, actual warfare breaks out (identified by the arrows). At the first outbreak, a "green" capability must function in a "green" environment, which it does, and subsequently survives to produce two replacement capabilities, "green" and "gray-green". Some time after this, another war breaks out, but now the environment has moved on from "green" to "gray": the "green" capability is wiped out (its succession line goes nowhere), but the "gray-green" capability survives, subsequently producing a replacement "gray-green" capability and a new "almost gray" capability. Shortly after that, another war breaks out, but by this time, the environment has changed radically (from gray to white to blue and almost back to green) and neither capability is viable: the species goes extinct. The lower diagram represents a situation in which a more rapid process of innovation (experimentation) has decreased the generation time of new concepts and has been able to inform the development of new capabilities, while keeping up with rapid changes in the environment. The same wars break out, but now the population is equipped with a more diverse set of capabilities. The wars act as "natural selection" to

[118]Peter P. Perla, *The Art of Wargaming*, p. 155.

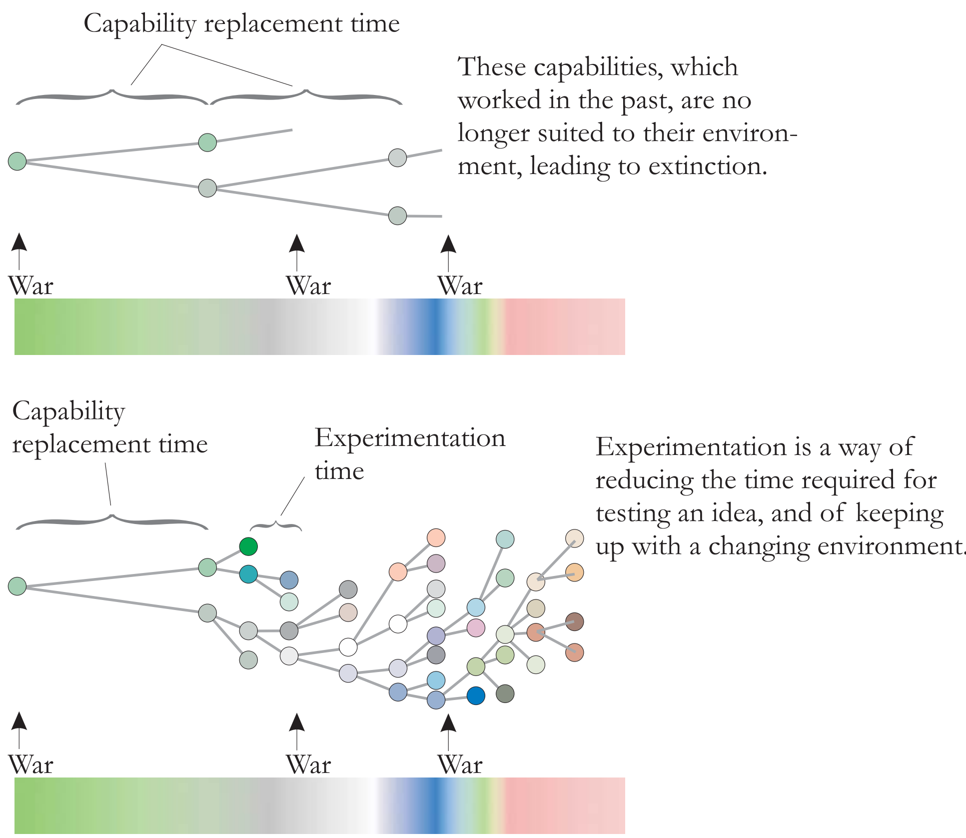

Figure 22: Increase in diversity and the reduction in generation time brought about by military experimentation in an evolutionary framework

eliminate the "unfit" capabilities, leaving the fittest to survive and produce new generations. The experimentation process is a way of speeding up the "natural selection" of the capability set (or force structure) to keep pace with the changing environment.

7 Cultural Issues in Innovation

7.1 Top-down vs Bottom-up Innovation

Military innovators sometimes speak of "top down" and "bottom up" innovation.[119] In our evolutionary model, "top down" innovation would refer to the process of looking for trends in the environment in which a system will be used, using these trends to predict a plausible future environment, and then identifying ways in which an existing system will fail to perform in that future environment or ways in which a future system ought to perform. These failures or enhancements of performance are called capability gaps. Similarly, "bottom up" innovation focuses on emerging new technologies and suggests how these can be used in either the current environment or future environment to enhance existing functions or perform new ones. All these aspects of top-down or bottom-up innovation are captured by the evolutionary model.

7.2 The Role of Leadership

Leadership is sometimes espoused as being a prerequisite for successful military innovation. For example, Williamson Murray highlights the crucial role played by Air Marshal Sir Hugh Dowding during the successful innovation of the Royal Air Force during World War II, highlighting his "great vision, leadership, and technological sophistication."[120] Such leadership is naturally associated with what is called a "top-down" process. Murray introduces a note of caution about the desirability of strong leadership, highlighting the fact that strong leadership in the wrong direction can have "a *disastrous* impact on the process of innovation."[121] He cites the cases of French Generals and the RAF Bomber Command who led their respective countries to positions of clear inferiority compared to the Germans at the beginning of World War II.

7.3 Speed of Change

Speed is sometimes seen as a desirable quality for change. Some thinkers desire revolutionary, or transformational, change, along the lines shown in figure 23 at left. On a superficial viewing, such a diagram indeed seems to highlight the desirability of a situation in which our capabilities are overwhelmingly superior to those of the enemy. However the view can be criticised on a number of fronts. It is very unlikely that a revolutionary

[119] Dean K. Bowley and Michael J. Brennan, *Innovation and Exploration: The Purpose and Characteristics of Military Experimentation*, Australian Defence Force Journal, 152, January/February, 2002.

[120] Williamson Murray and Allan R. Millett, *Military Innovation in the Interwar Period*, Cambridge University Press, 1996, p. 118

[121] Ibid. p. 308.

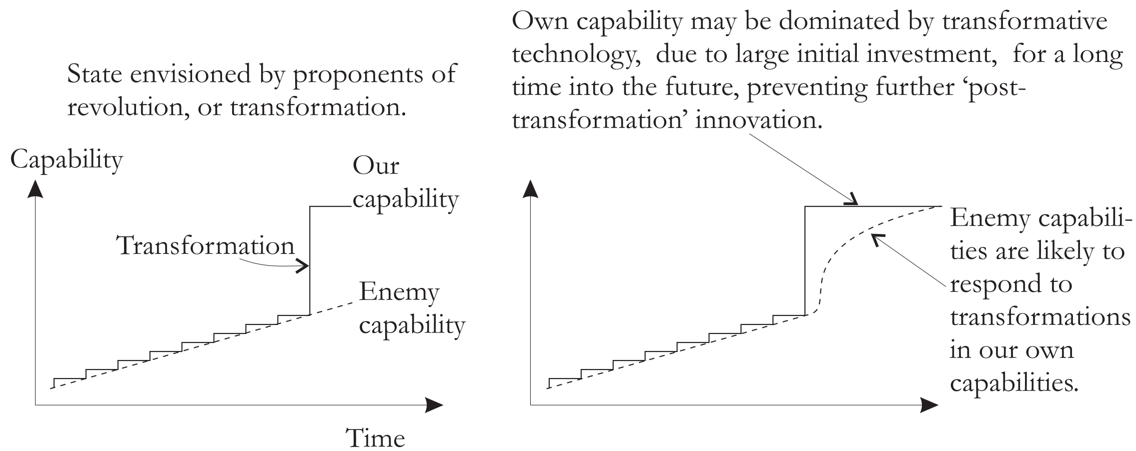

Figure 23: A view of the desirability of transformational or revolutionary change

advance would be made without large initial costs, or without being noticed by the enemy. If the advance is made as a result of a large initial investment, like the Manhattan Project's development of the atom bomb, for example, then users of the capability will likely want to continue relying on it for a long time into the future, during which time the enemy may adapt to the environment produced by the transformation. In the case of the atomic bomb, it has only been used twice in warfare, and yet nuclear weapons became a strategic asset, and were relied upon during at least the forty year period of the Cold War, and remains a threat of ultimate sanction in many countries' arsenals. Similarly, if a transformative innovation is noticed by an enemy, it is likely that they will either adopt the innovation themselves (at a lower cost, perhaps, because they will not have the same level of associated research and development costs), or they will adapt their posture to minimise the effect of the transformation. In the first case, the environment will become one of an arms race in which the two sides will co-evolve along similar symmetric lines. In the second case, the enemy will develop what are called asymmetric capabilities, leading to an environment that was not envisioned by developers of the initial transformation. Either way, the situation will become one illustrated by the right hand diagram in figure 23. Another example of an enemy response diminishing the transformative effect of a new technology is furnished by the case of the Allied response to German V-1 attacks during World War II, discussed in section 3.2.4.2 on p. 20.

7.4 Optimisation

As stated in section 2.2.3 (page 8), in some cases there are many equally valid ways for a system to occupy an ecological niche (biological or technological). Optimisation is sometimes achievable if the system can be well characterised and if the success measure has suitable properties. Evolutionary processes may achieve an optimal state, but in general the system is too multi-faceted to have any simply identified optimum. We may be able to identify traits that, in general, lead to a functionally successful system, but may not be able to specify a single, optimal system. Evolutionary processes throw up solutions that are sufficient. An example in the evolution of technology is furnished by

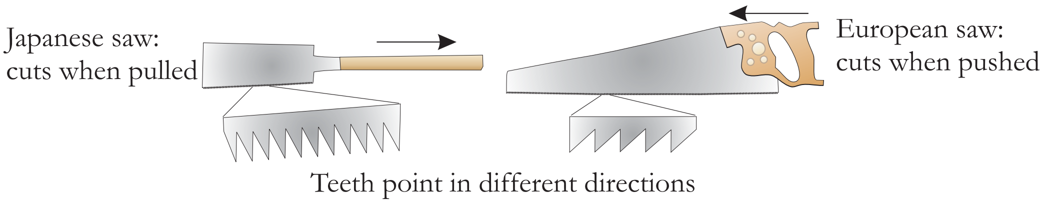

Figure 24: Functionally equivalent solutions to the problem of cutting wood: the Japanese and European saw evolved independently to cut in opposite directions

the Japanese woodworking saw, which, isolated from the evolution of European saws, evolved to cut when pulled rather than when pushed (see figure 24). The teeth of a Japanese saw point in the opposite direction to those of a European saw, and the saw blade is made out of thinner metal because it cuts under tension, rather than compression. European and Japanese saws are alternative solutions to the problem of cutting wood; both are sufficiently effective. Other examples of divergent solutions to the same problem are provided by (1) the knife and fork *versus* chopsticks for getting food from a container to the mouth (2) the Chinese wheelbarrow (a frame balanced above a large central wheel) *versus* the European wheelbarrow (a receptacle levered against a wheeled fulcrum) for transporting heavy and bulky material, (3) arched *versus* suspension bridges. (A biological example is furnished by the many designs for eyes (see figure 8) for providing useful samples of light to the brain.) Design competitions recognise this feature of technology and use it to promote a diverse range of solutions that can be evaluated against a number of functional criteria. The evolutionary requirements that intermediate forms must still be functional, and that any design must trade off conflicting properties also lead to solutions that are sufficient yet may be sub-optimal in certain aspects.

7.5 *Blitzkrieg* as Evolution

Blitzkrieg is used by some military thinkers as an example of revolutionary change. Murray cites the case of the interwar years to caution against this view.[122] He traces changes in French and German tactical systems over a twenty year period, and characterises both as evolutionary. Yet the cumulative, incremental nature of the changes in these systems culminated, by 1940, "in a chasm ... between how the two forces thought about, prepared for, and executed" battle. This is evidence that evolutionary change can lead to large scale dramatic change in military doctrine. In this paper, we have emphasised the evolution of the technological artifact. The question of whether resulting sociological or behavioural changes (or doctrinal changes in the military domain) are well described by the evolutionary mechanism is one for further research.

7.6 The Experimental System

We have broken down the evolutionary mechanism into two components (1) replication with variation; and (2) competition for survival in an environment. Either one of

[122]Ibid. p. 309.

these factors operating alone is insufficient to produce evolutionary change. Replication with variation alone would lead to explosive diversity and unsustainable growth. Such a condition would only prevail for short time-scales when resources are effectively unlimited (during times of total war?). Conversely, competitive selection acting without the mechanism of replication-with-variation perhaps comes closest to the condition desired by people who call for revolutionary change. As argued in this paper, such calls fly in the face of innovations that have actually proved most useful in the past, and assume that past experience (even derived from the crucible of actual war) is no guide to the future. There is also a difficulty in finding successful concrete examples of innovations that were not based on prior material. The case study above on Watt's steam engine revealed at least one case in which an innovation often seen to be revolutionary in fact fitted well within an evolutionary description. The market for abstract art and clothing fashions are perhaps good examples of systems driven by competitive selection without replication-with-variation. In both these systems, new generations arise by deliberately avoiding any connection with old-fashioned, *passé* ideas.

We can view technological and scientific systems as examples of *experimental* systems. By an experimental system, I mean one in which selection takes place. Experimental systems are evolutionary if they also display replication-with-variation. Social responses to technological change may or may not be experimental (i.e. have well defined selection rules). Military ones (doctrine, training, tactics, strategies) are more likely to be experimental; whether they are evolutionary may be a topic for further research. That is, evidence must be gathered to address the question of establishing if social responses to innovation can be described by replication-with-variation.

8 Conclusion

We have presented a general evolutionary model of innovative systems. It was shown how such a model, originally applied to biological organisms, can also be applied to any system of competing diverse replicators. Such systems include military systems, which are generally based on previous systems (replication) but with variation. We have seen how such an evolutionary model can also be applied at two levels to science: at one level, science can be seen as an evolutionary method of refining competing theories using experimentation as a survival test; at another level, we have seen how philosophies of science have developed historically according to evolutionary principles. Along the way, we have drawn some lessons about how science does and does not work, and applied these to the process of military experimentation.

When considering balance of investment decisions, the assumption is sometimes made that there is an optimum investment balance and an optimum force/capability mix. But it may be better to assume there is no optimum balance for a defence force with flexible applications, and many acceptable measures of effectiveness in each application. Using our evolutionary model of military concept development and experimentation, it may be better to structure an experimental program so that its output consists of a set of statements that: (1) relate to feasible concepts used in realistic future environments, (2) are supported using robust and diverse assessment methods, and (3) leave final balancing decisions to the top level investment decision makers.

Acknowledgements

Thanks go to Drs. Matthew Fewell and Stuart Sutherland for many interesting discussions and for their comments on this paper. I also wish to thank Dr. Chris Davis for the initial impetus to write a framework paper on experimentation.

Appendix A Details of Coloured Dot Evolutionary System

The potential number of reproductive survivors S_t of the generation at time t is given by

$$S_t = \sigma_t N_t \,, \tag{A1}$$

where N_t is the number of dots in the generation at time t, and σ_t is given by

$$\sigma_t = \exp(-N_t/P)\exp(-\bar{D}_t/C)\,, \tag{A2}$$

where P and C are constants, and $\bar{D}_t$ is the mean colour discrepancy for the population. The factor containing N_t prevents continual population growth, and can be interpreted as reflecting competition for limited resources. The mean colour discrepancy for the population is given by

$$\bar{D}_t = \frac{1}{N_t}\sum_{i=1}^{N_p} D_i \,, \tag{A3}$$

where

$$D_i = (r_i - r_t)^2 + (g_i - g_t)^2 + (b_i - b_t)^2 \,, \tag{A4}$$

r_i, g_i, b_i, are the red, green and blue colour components of dot i, respectively, and r_t, g_t, b_t, are the red, green and blue colour components of the environment at time t, respectively. For each generation, the actual dots that potentially replicate (the parents) are the S_t dots that have the least colour discrepancies D_i. Having chosen the dots that can potentially replicate, the actual replication proceeds as follows. Each of the S_t parent dots at time t is assigned a random number O_j, of offspring $j = 1, \ldots, S_t$. The random number is chosen from a uniform distribution between zero and O_{max} ($O_{max} = 4$ in figure 1). The colours of the O_j offspring at time $t+1$ of parent point j at time t are set equal to the parent colour with a random additive variation, as follows:

$$r_{j,k,t+1} = r_{j,t} + \mathcal{N}(0, v) \tag{A5}$$
$$g_{j,k,t+1} = g_{j,t} + \mathcal{N}(0, v) \tag{A6}$$
$$b_{j,k,t+1} = b_{j,t} + \mathcal{N}(0, v) \tag{A7}$$
$$j = 1, \ldots, S_t, \quad k = 1, \ldots, O_j, \tag{A8}$$

$\mathcal{N}(0, v)$ represents a random number chosen from a normal distribution with mean zero and variance v. The variance is chosen by trial and error to produce a large enough population to survive the first slow environmental transition, yet not so large that the computing time for the entire run becomes inconvenient.

Appendix B Code for Coloured Dot Evolutionary System

```
function duration = evolvecoloureddots_report(tstep,colour_var,plot_parent_children_lines)

% duration = evolvecoloureddots3(tstep,colour_var,plot_parent_children_lines)
%
% Tstep and Colour_var default to 5 and 0.05, respectively.

% Modified to use all three components of colour environment, not just the
% dominant colour.

% A. Knight 2003

if nargin==0
    tstep = 5;
    colour_var = 0.05;% allowed variation in colour components
elseif nargin==1
    colour_var = 0.05;
end
if nargin<3
    plot_parent_children_lines = 0;
end

set(gcf,'defaultaxesfontsize',14)
set(gcf,'defaulttextfontsize',14)

set(gcf,'color',[1 1 1])

Ndots = 100;
xdots = zeros(1,Ndots);
ydots = rand(1,Ndots);
maxchildren = 7; % number of children for each individual
space_var = .05; % allowed variation in spacial location of children relative to parents
marker_size = 12;
t = 1:100;
this_t = 0;
N = length(t);
% Use colormapeditor to generate the colour map:
sum_colours = map4;
clf
ax_environment = axes('pos',[.1 .1 .8 .1],'nextplot','add','visible','off','xlim',[0 100]);
imagesc(1:length(sum_colours))
colormap(sum_colours)
ax_population = axes('pos',[.1 .2 .8 .5],'nextplot','add','visible','off','xlim',[0 100]);
ax_population_size = axes('pos',[.1 .7 .8 .25],'nextplot','add','visible','off','xlim',[0 100]);


% Initial population:
colours = ones(Ndots,1)*sum_colours(1,:);
colours(colours>1)=1;
colours(colours<0)=0;

xdots_prev = xdots;
ydots_prev = ydots;

% At each time step, find the top s percent of present population to reproduce, based on
```

```
% individual closeness to the present colour.
Nsurv = length(ydots);
dotmarkersize = 10;



while this_t<=N-tstep & Nsurv>0
    Ndots = length(ydots);

    set(gcf,'currentaxes',ax_population_size)
    plot(this_t,Ndots,'.','markersize',dotmarkersize,'markeredgecolor',[0 0 0])
    text(this_t,Ndots,[' ' int2str(Ndots)])

    set(gcf,'currentaxes',ax_population)

    this_t = this_t + tstep;

    % Find present colour:
    [dum,ind]=min(abs(this_t - t));

    this_colour = sum_colours(ind,:);
    % calculate each individual's least square colour discrepancy from the present colour:
    red_dist2 = (colours(:,1) - this_colour(1)).^2;
    green_dist2 = (colours(:,2) - this_colour(2)).^2;
    blue_dist2 = (colours(:,3) - this_colour(3)).^2;
    tot_dist = sqrt(red_dist2 + green_dist2 + blue_dist2);
    [tot_dist_sorted,dist_sort_ind] = sort(tot_dist);

    % survival rate is inversely proportional to the population...
    s = exp(-Ndots/100);
    % and inversely proportional to the colour discrepancy
    s = s*exp(-mean(tot_dist)*3);
    Nsurv = fix(s*Ndots);
    if Nsurv==0 | length(ydots)==0
        disp(['No survivors, extinction occurred at t = ' num2str(this_t)])
        duration = this_t;
    else
        dist_sort_ind = dist_sort_ind(1:Nsurv);
        ydots = ydots(dist_sort_ind);
        xdots = this_t*ones(size(ydots));
        colours = colours(dist_sort_ind,:);
        Ndots = length(ydots);
        % Generate the children:
        xdots_parent = xdots;
        ydots_parent = ydots;
        ydots = [];
        newcolours = [];
        %line_colour = [180 121 94]/255;
        line_colour = [1 1 1]*200/255;
        for i=1:Ndots
            Nchildren = fix(maxchildren*rand);
            %Vary the colours based on the parent:
            rgb=colours(i,:);
            r = rgb(1)+colour_var*randn(1,Nchildren);
            g = rgb(2)+colour_var*randn(1,Nchildren);
            b = rgb(3)+colour_var*randn(1,Nchildren);
            childrencolours=[r' g' b'];
            childrencolours(childrencolours>1)=1;
```

```
            childrencolours(childrencolours<0)=0;
            % Position the children near the parent:
            ychildren = ydots_parent(i)+space_var*randn(1,Nchildren);
            ydots = [ydots ychildren];
            if plot_parent_children_lines==1
                %Plot parent-children lines:
                for k=1:Nchildren
                    h = plot([this_t-tstep this_t],[ydots_parent(i) ychildren(k)],'-');
                    set(h,'color',line_colour,'linewidth',.2)
                end
            end
            for k=1:Nchildren
                plot(this_t,ychildren(k),'o',...
                    'markerfacecolor',childrencolours(k,:),...
                    'markeredgecolor',0.9*childrencolours(k,:),...
                    'markersize',marker_size)
            end
            if this_t==tstep & Nchildren>0
                plot(this_t-tstep,ydots_parent(i),'o',...
                    'markerfacecolor',rgb,...
                    'markeredgecolor',0.8*rgb,...
                    'markersize',marker_size)
            end

            % assemble new colours matrix for the next cycle
            newcolours = [newcolours ; childrencolours];

        end
        disp(['Time = ' num2str(this_t) ', ' ...
                'Number of dots is now ' int2str(length(ydots)) ', ' ...
                'mean colour discrepancy is ' num2str(mean(tot_dist)) '.' ])
        % Plot final population number
        if this_t==N
            set(gcf,'currentaxes',ax_population_size)
            plot(this_t,length(ydots),'.','markersize',dotmarkersize,'markeredgecolor',[0 0 0])
            text(this_t,length(ydots),[' ' int2str(length(ydots))])
        end

        colours = newcolours;
    end
end

if plot_parent_children_lines==1
    % Put the heritance lines behind the dots:
    set(gcf,'currentaxes',ax_population)
    h_all = get(gca,'children');
    h2=findobj(gca,'color',line_colour);
    h1 = setdiff(h_all,h2);
    set(gca,'children',[h1 ; h2])
end
set(gcf,'render','zbuffer')
set(ax_population,'ylim',[-inf inf])
set(ax_population_size,'visible','on','xtick',[],'ylim',[0 inf])
```

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A. Knight

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19. ABSTRACT

This paper presents an evolutionary view of technological and scientific innovation, and describes the role of experimentation in both. A stated policy for the Australian Department of Defence (reflecting the defence policies of other countries, including the United States) is to use the methods of empirical science to inform the innovation of the Defence Force. This paper describes what might be meant by “the methods of empirical science”, and how such methods might be employed to improve military forces. We show how an evolutionary view both describes much of the scientific and technological innovation process, and provides guidance on how to move to the future. Historical case studies of technological and scientific innovations, and structural considerations, are used to justify such a view. A description of some of the tools of military experimentation is given, and it is shown how these fit within an evolutionary framework. Finally, the evolutionary framework is used to analyse some of the perennial debates about innovation, such as the role of revolution, the place of leadership and the search for optimal solutions.